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Comparative effectiveness of tightening techniques for A490 1 1/4 inch diameter bolts

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COMPARATIVE EFFECTIVENESS OF TIGHTENING TECHNIQUES FOR A490 1¼ INCH DIAMETER BOLTS

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ABSTRACT

Slip critical joints require the reliable pre-tensioning in a connection. As high-strength bolts get larger and the redundancy is reduced, the need for an accurate tightening technique becomes more important.

Using an A490 1¼ inch diameter bolt, the Turn-of-Nut Method, the Direct Tension Indicator Method #1 with the Load Indication Washer underneath the head of the bolt, and the Direct Tension Indicator Method #2 with the Load Indicating Washer next to a hardened washer under the nut were examined. Other variables were oiled versus greased (waxed) threads, vertical versus horizontal plates, and long versus short grip bolts.

The results showed that the Turn-of-Nut method was the most accurate, easiest, cheapest and the least time consuming of the above mentioned methods. The Direct Tension Indicator Method #2 successfully reached the minimum pre-tension for only the short bolts. It was also the most expensive of the three methods. The Direct Tension Indicator Method #1 proved to be unreliable for both bolt lengths, since it did not reach the minimum required pre-tension.

Another noteworthy conclusion was that the AISC specified time of 10 seconds to tighten the bolts with an impact wrench is too short for these large diameter bolts. This time should be increased and depend on the bolt diameter and length.

1. INTRODUCTION

Design engineers depend on fabricators and constructors to build large structures according to the plans that they have developed. The designers assume that everything will be built according to their specifications. The connections are carefully detailed because their proper behavior is critically important for the successful erection and occupancy of a building. During the construction, the erector has the most influence on the connection, and he must ensure that these critical components reliably meet the designers requirements. Failure to do so could lead to catastrophic consequences. This is especially important for slip critical and direct tension connections. A number of techniques exist so that the erector can attempt to ensure the integrity of these joints.

It is crucial for slip critical connections to be fully tightened. A bolt is fully tightened when the tension is at least 70% of the ASTM specified minimum tensile strength of the bolt. Though not all types of joints must be fully tightened, AISC requires the following connections to be treated as slip critical:

1. Joints subjected to fatigue loading.
2. Joints with bolts installed in oversized holes.
3. Except when otherwise noted, joints with bolts installed in slotted holes.
4. Joints subject to significant load reversal.
5. Joints in which welds and bolts share in transmitting load at a common faying surface.
6. Joints in which any slip would be critical to the performance of the joint

or the structure.

Bolts in direct tension must also be fully tightened to ensure a safe connection and minimize the change in force in the bolt during service.

As new types of higher strength steels are developed, larger and stronger bolts are being used with increased member sizes. Bolts meeting the ASTM A490 specification, hereafter referred to as the A490 bolts, have become very popular. Diameters over one inch are now widely used in building construction. Most testing on bolt behavior during tightening has been performed using smaller diameter bolts, and the results have been extrapolated to larger diameter bolts and used in establishing specification requirements[1].

2. BACKGROUND

During the construction of the Embassy Suites Hotel in New York City, Atlas-Gem Erectors had many problems with the project, which specified Direct Tension Indicator Method with Load Indicating Washers to tighten the A490 1¼ inch diameter bolts. These problems lead to this testing program of the comparative effectiveness of the Turn-of-Nut and Direct Tension Indicator bolt tightening techniques.

Since the approval of the first high-strength bolt specifications by the Research Council on Riveted and Bolted Structural Joints (RCRBSJ) in 1949 there have been concerns of insuring that the bolts are properly tightened[2]. Methods have been developed and improved upon after much use[1]. However, everything developed has had its problems, and nothing is foolproof.

There has been a significant amount of testing on high-strength bolts and the techniques used to tighten them. Some of the research done is as follows. An extensive study done at Delft University in the Netherlands detailed many different tightening methods including the Turn-of-Nut as well as the Load Indicating Washers. This study detailed the advantages and disadvantages of the different techniques[3]. The significant influence of lubrication on the bolt threads was pointed out by Lynn Eaves in 1978[4]. James Notch showed that hardened washers were needed for the proper tightening of large diameter bolts, as well as as well as the need for a uniform "snug" condition[5]. Early testing on the load indicating washers on bolts in the vertical position was done in 1973 by Struik, Oyeldum, and Fisher[6]. This testing proved the validity of the washers as load indicators. In 1987, Kulak, Fisher, and Struik published the second edition of the **Guide to Design Criteria for Bolted and Riveted Joints** with the accumulation of much of the previous work done on bolts and bolt tightening techniques[1]. The information on bolt properties and installation contained in this book was extensively used in the course of this investigation.

3. OBJECTIVES

The research program explored the techniques and relative merits of the Turn-of-Nut and the Direct Tension Indicator Methods of tightening A490 1¼ inch diameter bolts. The Direct Tension Indicator Methods for this program used the load indicating washer. The objective of the study was to determine the effectiveness of the two tightening techniques and if the extrapolation from small bolt testing is valid for such large diameter bolts. A sampling of all the materials used in the tests including the bolts, hardened washers, and load indicators had been checked to insure they complied with the applicable ASTM specifications.

4. TEST PROGRAM

As previously mentioned, the purpose of the research program was to determine the effectiveness of the Direct Tension Indicator and the Turn-of-Nut tightening techniques in achieving the required pre-tension under a number of variables. One method that was considered but not examined was the direct tension loading system. The direct tension loading device cannot be used with A490 1¼ inch diameter bolts since the bolts, especially the shorter ones, are not ductile enough to handle the necessary excess pre-load or pre-elongation from the loading device. This pre-load is needed to load the bolt over the required pre-tension in order to compensate for its elastic "snap back"once the device transfers the load to the bolt[7]. Also, in most applications for building construction, the direct tension loading device is too bulky for a joint with closely spaced bolts.

The program was divided into two groups including pre-testing and testing. The purpose of the pre-testing was to identify the load-strain curve of the bolts and to insure that all the materials met specification requirements.

4.1 Pre-testing:

Two lengths of bolts, designated as long and short, and will be described later in the report were to be tested. The pre-testing developed load-strain curves for the two lengths of 1¼ inch A490 bolts. The first tests loaded the bolts in a direct tension machine which could apply a force up to 300 kips. The bolts were loaded to failure. In conjunction with the direct tension tests, the bolts were also tested in a Skidmore-Wilhelm Tension Calibrater to determine the strain-tension relationship of the bolts using the torque/tension loading effect of the impact wrench. The Skidmore-Wilhelm, which is a tension measuring device, was also used to insure that the impact wrenches were capable of tightening the bolts.

Pre-testing also determined whether all the pieces of the bolt assemblies conformed to the applicable ASTM standards. The bolts' yield and ultimate strengths were checked to insure they satisfied the specifications. The hardened washers as well as the load indicator washers were tested for hardness.

4.2 Testing:

There were seventeen tests in this program. Each test included twelve bolt assemblies in order to give enough data to allow for conclusive observations to be made about the different tightening techniques. Each bolt assembly consisted of one bolt, one nut, two hardened washers and, for some tests, a load indicator washer. The bolts, nuts and washers came from a variety of American manufacturers. A36 steel plates with oversized holes formed the connecting material for the joint. Eight 1½ inch plates were used for the long bolts [Fig. 1] while three 7/8 inch plates were used for the short grip bolts [Fig. 2]. A36 steel was chosen since it is the lowest strength material that would use an A490 bolt.

Each experiment had a change in one of the following variables:

1. Tightening techniques
   a. Turn-of-Nut
   b. Direct Tension Indicator Method #1
   c. Direct Tension Indicator Method #2
2. Bolt length
   a. Short bolt length
   b. Long bolt length
3. Plate orientation
   a. Vertical plates
   b. Horizontal plates
4. Thread condition
   a. Greased
   b. Lightly oiled

In addition to the previously cited variables, two different brands of impact wrenches were used in each test. They were two of the largest one-man impact wrenches commercially available. J & M Turner, Inc., the manufacturers of the load indicating washer used in this testing, recommended the CP-614 to tighten the A490 1¼ inch diameter bolts[8]. The Cleco W-2119 was also chosen because it had the required torque capabilities for tightening these bolts. It was selected in addition because Cleco products had already been used in previous bolt tightening studies. The impact wrenches were fed a steady supply of air at approximately 90 PSI through a ten foot hose that had a ½ inch inside diameter.

The reasons for choosing the variables were to cover many possible variations that could occur at a construction site, as well as to perform parallel testing. Parallel testing insured that each technique could be systematically compared with its counterparts, thus ensuring a complete review of the techniques' behavior subject to each variable condition.

4.2.1 Tightening Techniques:

The Turn-of-Nut method uses the "snug" condition as the first step in the tightening process. "Snug" is defined as the condition reached when the plies of the joint are in firm contact. This is achieved by either a few impacts of an impact hammer or the full effort of a man on a spud wrench. Each bolt was tighten to "snug" before the next step was taken. The joint was tightened starting with the bolt at the most rigid end of the joint and working around to the less rigid end. After snug, the installer marks the bolt assembly with the required rotation with paint or crayon. This rotation depends on the diameter to under-head-length ratio of the bolt. The under-head-length is everything beneath the head of the bolt including the grip length and the threads. Short bolts, those up to a ratio of four, receive a one third turn. Medium bolts which have a ratio between four and eight and were not used in this experiment get a one half turn. A long bolt which has a ratio of more than eight receives a two thirds turn. Each joint tightening sequence was the same as for snug.

The Direct Tension Indicator methods follow similar initial tightening steps as the

Turn-of-Nut method. First the bolts were tightened to the "snug" condition. This was to ensure that all the bolts were carrying a portion of the load and that the plates were close together. If this step were not done, the load could be unevenly distributed, since the first bolts would loosen when the later bolts were tightened.

The Direct Tension Indicator methods used a load indicator washer. The load indicator washer [Fig. 3] is a washer with "dimples" or protrusions which flatten as the bolt assembly is tightened. The desired load is reached when the washer's dimples were at the prescribed height. A feeler gage was used to check the washer to ensure that it had reached the minimum allowable height. For the A490 1¼ inch diameter bolt, the load indicator washer has eight dimples, four of which must not allow the feeler gage to pass through in order for the system to pass inspection.

Direct Tension Indicator Method #1 had the load indicator washer underneath the head of the bolt and used a .015 inch thick feeler gage. The Direct Tension Indicator Method #2 used a .005 inch feeler gage, and the load indicator washer was placed under the nut with a hardened washer between the nut and the load indicator.

4.2.2 Bolt Length:

A critical variable is the bolt length. The bolt length is defined as the length from under the head to the end of the bolt. The two bolt lengths chosen for this procedure were approximately five inches (four diameters) and fourteen and one quarter inches (twelve diameters) [Fig. 4]. These lengths represented both ends of the spectrum for common lengths. At under four times the diameter, the five inch bolt is a short bolt. With the short bolt, the Turn-of-Nut method requires only a one third turn of the nut after the snug condition (as defined earlier). The joints for the short bolts were made with three 7/8 inch A36 steel plates.

The fourteen and one quarter inch long bolt is over eight but less than twelve times the diameter of the bolt. This length requires a two thirds turn of the nut after the snug condition for the Turn-of-Nut method. For the long bolts, eight 1½ inch A36 steel plates were used for the joints.

4.2.3 Plate Orientation:

The plates were tested in both the vertical and horizontal position in order to simulate usual construction site conditions. The vertical position was closely scrutinized, because uncertainty existed whether the results would be affected by the washers hanging on the bolts between the threads which could cause the nut and washers to bind, or by the bolts lying on the plates which could cause eccentric loading. The tightening sequence for the vertical joints started on the bottom row of bolts. First the center bolt in the row was tightened, and then the outside bolts on that row were tightened before moving to the second row. Fig.

6 shows the vertical plate tightening sequence. When the plates were horizontal the sequence was started from the inside of the joint and radiated outward as shown in Fig. 7.

4.2.4 Thread Condition:

The conditions of greased and lightly oiled threads were included because the installation of the bolts with the Direct Tension Indicator Methods required grease. J & M Turner's[8] recommended Chem-Trend Stick Wax 140 was used to lubricate the threads of the bolts. The greased condition is also commonly referred to as a waxed condition. For continuity in this report the term greased will be used.

Normally, bolts coming from the manufacturer had a light coat of oil. However, the bolts could not be used in the "as received" condition with the manufacturer's coating. After preparing the bolts for the strain gages, many steel shavings adhered to the bolt due to the manufacturer's oil. Therefore, the oil had to be removed. The "as received" condition was simulated by lightly oiling the threads with a machine oil before they were put into the joint. In order to do effective parallel testing both conditions were used for the Turn-of-Nut method and the Direct Tension Indicator method.

4.3 Test Designation:

A listing of each of the tests and their variables is given in Table 1. Each test is labeled with a series of letters. These letters indicate the variables of the test. The letters indicate the following variables:

T: Turn-of-Nut

D1: Direct Tension Indicator Method #1

D2: Direct Tension Indicator Method #2

S: Short bolt length

L: Long bolt length

G: Greased threads

O: Oiled threads

V: Vertical plate orientation

H: Horizontal plate orientation.

5. MATERIAL PREPARATION

The same procedure was followed in the preparation of each bolt so that the strain gage application on the bolt was consistent. First, the bolt was machined. The machining process included the installation of cone shaped holes drilled into the center of the head and the bottom of the bolt. These holes were for a C-clamp dial gage [Fig. 5] to determine the bolt elongation at the same point for each measurement. Two flat areas were milled on opposite sides of the shank directly beneath the head of the bolt.

Two eighth inch Micro-Measurement strain gages were then epoxied to the bolt on each of the flat areas. The data from both strain gages were needed for one bolt's strain reading. Each bolt's strain gage measurements were averaged in order to compensate for any bending effect that may have existed during the tightening.

Small holes were drilled completely through the head to the milled flat areas. These holes were for the strain gage wires. The wires connected the gages to the Hottinger-Baldwin data acquisition system which displayed the strain measurement during the testing. Without the holes drilled through the head of the bolt, the plates may have cut the wires during the tightening procedure. The strain gages in conjunction with the Hottinger-Baldwin were the primary source of measurements for the testing. The dial gage was a secondary measurement source and used only to confirm the strain gages. The strain gage continually measured the strain rather than intermittently like the dial gage, which had to be removed each time the bolt was tightened.

The A36 steel plates which made up the connected material were drilled with standard over-sized holes. Each plate was drilled separately to best simulate a field connection at a construction site. There was concern that if the holes were drilled through a stack of plates at the same time, then the joint would be too neat and therefore align unrealistically.

6. TEST PROCEDURE

Each test went through the same procedure to insure consistency in the testing. After 12 bolts were drilled and gaged the heads were numbered with paint or permanent Magic Marker. The wires coming from the head of each bolt were connected to cables coming from the Hottinger-Baldwin. The threads were either oiled or greased as dictated by the variable being tested at the time. The bolts were then placed into the steel plate set up [Fig. 8]. The steel plates were set up on one beam for testing with vertical plates [Fig. 9] and between two beams for testing with horizontal plates. They were set on two beams for the latter so that the bolt heads could hang freely without the interference of a supporting beam. One inch by one inch steel angle sections, together with clamps, were used to secure the plates to the beams. The gages were then checked to insure all the gage connections were working properly and the Hottinger-Baldwin was reading the gages.

A measurement of the bolt length was taken before the bolt experienced any load by both the dial gage and the strain gages. The bolts were then tightened to "snug". The "snug" condition was achieved by tightening the bolt with a torque wrench to 200 foot pounds [Fig. 10]. All 12 bolts were at 200 foot pounds in order to ensure that they were all at the same tightness in accordance with the AISC Specification[9]. In some cases this meant tightening all the bolts in sequence two or three times. A strain gage measurement was taken after the "snug" condition.

The impact wrench was then used to start tightening the bolts. A strain gage reading was taken after the ten seconds of tightening by the impact wrench on one bolt, since AISC's *Specification for Structural Joints Using ASTM A325 or A490 Bolts*[9] requires that a bolt be tightened in approximately ten seconds.

The tightening then resumed with the impact wrench until the bolt was "tight". "Tight" depended on which one of the tightening techniques was being tested. For the Turn-of-Nut method "tight" was after the prescribed rotation was complete. For the Direct Tension Indicator "tight" was after the feeler gages did not pass by 4 dimples on the load indicator washer. The impact wrench had to be stopped during the tightening process to determine if the dimples had been flattened to the necessary height. The stop watch which timed the impact wrench was also stopped. The dimples were checked, and then the tightening process resumed if the bolts were not "tight". This process was repeated until all the bolts were tightened. The first six bolts in each test were tightened with the CP-614, and the last six were tightened with the Cleco W-2119. Dial gage and strain gage measurements of all twelve bolts in the connection were then taken.

The bolts were then completely unloaded to a point where the nuts could be loosened by hand. A final strain gage measurement was taken after the bolts were unloaded to check if any inelastic or permanent deformation had occurred during the tightening process.

After the last reading the wires were cut approximately two inches from the head of the bolt. The excess wires were left in the event there would be more testing done using these bolts and gages in the future.

7. RESULTS

7.1 Pre-testing:

Both impact wrenches were capable of tightening the bolts. However, neither could tighten the bolts to the requirement of ten seconds or less. The CP-614 wrenches, which were not new, were slower in tightening the bolts than the Cleco W-2119, which was new. Two CP-614 wrenches failed early in the testing, but a reconditioned CP-614 did complete the tests without any problems. The new Cleco W-2119 was used without any problems through out the entire test program.

The direct tension pre-tests developed the elastic load-strain curves for both of the A490 1¼ inch diameter bolts as seen in Fig. 11. It also verified that the short bolts satisfied the requirements of ultimate stress between 150 and 170 ksi. The measured ultimate stress was 171 ksi and 168 ksi. The long bolts had a higher ultimate stress of 199 ksi and 201 ksi, and hence exceeded the permissible tensile strength of the A490 bolt. No measurements were taken between the elastic zone and the stress at which the bolt failed. The pre-tests using the impact wrench and the Skidmore-Wilhelm verified the elastic load-strain curve. However, the impact wrenches did not have the ability to exceed the bolt tension of 140 kips (144 ksi). Therefore, the torque/tension pre-tests could not duplicate the verification of the direct tension test's yield point of the bolts.

Hardness tests on the hardened washers showed that they all met the ASTM F 436-86 requirement of between 38 and 45 HRC as well as dimensional tolerances. The load indicator washers met with ASTM F 959-85 specifications so they were acceptable too.

The prescribed pre-tension for bolts is .70 times the tensile strength. For A490 1¼ inch diameter bolts the minimum specified tensile strength is 150 kips, therefore the pre-tension load is:

$$.70\ F_t = F_{pre\text{-}tension}$$

$$.70\ (150\ \text{kips}) = F_{pre\text{-}tension}$$

$$F_{pre\text{-}tension} = 102\ \text{kips}$$

The graph from the tension pre-tests (Fig. 11) indicate that the prescribed pretension of 102 kips, has a strain of approximately 2,500 µunits/unit.

7.2 Turn-of-Nut:

The Turn-of-Nut method showed some interesting results in this testing [Fig. 12]. For the long bolts, there was an upward trend for the final strain readings in the joint. The first in the sequence had a lower strain and consequently a lower load than the bolts which were tightened later in the test. The bolts with oiled threads exhibited more variable results than the greased threads. The final strain for the bolts had a greater scatter when the threads were oiled. When they were greased, the final strains were fairly close. .

Fig. 13 shows the frequency distribution of the Turn-of-Nut Method for long bolts. As it shows 27 of the bolts reached the minimum strain, while 20 did not. The Turn-of-Nut method for long bolts took an average of between 13 and 38 seconds to tighten the bolt [Table 2].

The short bolts reacted differently to the Turn-of-Nut method [Fig. 14]. After the recommended rotation, the short bolts had a very high strain which indicated a load higher than the specified 102 kips per bolt. However, there was a bolt which were not in the data point grouping. The point on the zero line indicate a failure of the strain gage. A number of reasons explain the failure. It could have been a cut in the wire, a problem with the epoxy properly adhering the gage to the bolt, or an incomplete circuit at the connector. The final strain readings show that none of the bolts were loaded into the inelastic zone since they all had no or low strains after they were unloaded. Also, considers that a pre-tension significantly greater than the prescribed pre-tension is acceptable. Like the long bolts, the short bolts' high final strains were lower when the threads were oiled than when they were greased.

Fig. 15 shows the frequency distribution for the Turn-of-Nut Method for short bolts. It shows 9 bolts did not reach the minimum strain reading, while 38 successfully reached the minimum stain reading. The time range for tightening the short bolts was between 16 and 37 seconds [Table 2].

The position of the bolts did not affect the final strain after complete tightening. There was not a noticeable variability between bolts tested in the vertical and horizontal orientation. This indicates that the Turn-of-Nut method is not effected by bolt orientation.

7.3 Direct Tension Indicator Method #1:

The results of Method #1 of the Direct Tension Indicator had some similarities to those of the Turn-of-Nut method. The bolts of the Turn-of-Nut method showed a propinquity to having higher strains later in the sequence of the testing for the long bolts. The increase of the final strains in Fig. 16 displays the same trend in tightening for the Direct Tension Indicator. Another similarity is that certain conditions of the bolt do not affect the final results. The plate orientation of vertical or horizontal had similar final strains. The variable with the greatest effect is the length of the bolt.

The variability of data points was small for the long bolts, therefore, the condition of the threads whether greased or oiled did not affect the final grouping of bolt strains [Fig. 16]. Only 3 of the long bolts reached the required strain, while 30 were too low [Fig. 17]. The time range for tightening was between 50 and 52 seconds [Table 2].

The short bolts' final strains are shown on Fig. 18. Like the long bolts using the Direct Tension Indicator, the thread condition of greased or oiled again did not affect the results of the final strains. There were a number of data points that were on the zero line which again show a failure in the strain gage.

The frequency diagram for short bolts tightened by the Direct Tension Indicator Method #1 is shown in Fig. 19. It shows that this method is not adequate for tightening the short bolts since 24 bolts did not reach the proper pre-tension, and only 17 reached the required minimum strain. The average time needed to close the indicator gap and bring the bolts to tight was between 26 and 36 seconds [Table 2].

7.4 Direct Tension Indicator Method #2:

The tests labeled D2-LGV2 in Fig. 20 and D2-SGV2 in Fig. 22 show the results of tightening by Direct Tension Indicator Method #2. Fig. 21 showed that 7 of the long bolt strain reading were lower than 2,500 μunits/unit. In Fig. 22 and Fig. 23 D2-SGV2 showed that all of the short bolts were tightened to over 2,500 μunits/unit.

The bolts with oiled threads reacted differently during the tightening procedure. While the bolts were being tightened, the load indicator washer slipped on the hardened washer and the entire bolt assembly rotated. An adjustable wrench was needed to prevent the bolt from rotation while the nut was being tightened.

Figures 12, 14, 16, 18, 20, and 22 are consolidated in Figure 24, so that all methods can be viewed and compared simultaneously.

8. OBSERVATIONS AND COMPARISONS OF TIGHTENING TECHNIQUES

8.1 Turn-of-Nut:

8.1.1 Advantages:

By far this method was cheapest, easiest, the most accurate, and the least time consuming to accomplish. Since there were fewer pieces, because no load indicator washer was needed, the bolt assemblies were the cheapest. The results in Table 3 shows the material cost for the Direct Tension Indicator methods compared to that for the Turn-of-Nut method. Secondly, tightening the bolt is the easiest since the markings for the rotation were clearly visible at all times on top of the wrench socket. The impact hammer operator could tell when the rotation was complete. Most of the bolts tightened by the Turn-of-Nut method did reach the proper pre-load for both bolt lengths. Therefore, this method was the most accurate of all the methods tested. It was less time consuming for both the time the impact wrench ran and the time for the whole procedure for tightening the joint [Table 2]. However, this time was greater than the AISC[9] specified time of ten seconds to tighten the bolt.

8.1.2 Disadvantages:

A drawback to the Turn-of-Nut Method is that getting the bolt to the "snug" condition must be consistent. The difference in final strains between greased and oiled threads, especially for the long bolts, showed that the plates were compacted more when the bolts were greased than when they were oiled. "Snug" depends on torque, and grease significantly reduces the torque during tightening.

A deficiency with the Turn-of-Nut Method is that the "snug" condition is not sufficient to bring all the plates into contact for a large number of plates. This can be seen in the difference between the final strains for the short bolts and the long bolts. The long bolts have a distinct upward tightening trend in the sequence of bolts. Bolts that were tightened earlier in the sequence had a lower strain than the bolts that were tightened later in the sequence. This indicates that when the first bolts are tightened, they bring the plates into full contact. Then when the later bolts are tightened, these bolts are able to be tightened more. This causes the earlier bolts to lose some of their pre-tension.

8.2 Direct Tension Indicator Method #1:

8.2.1 Advantages:

The only advantage to the Direct Tension Indicator Method #1 was that it had very consistent readings for all of the tests. The condition of oiled or greased threads did not have any bearing on the final strains. The position of the plates in the horizontal or vertical did not affect the final strains. The concerns about the washers getting caught in the threads or eccentric loadings were unfounded in these tests.

8.2.2 Disadvantages:

There are, however, many disadvantages to this system. Most importantly this method did not successfully bring all the bolts to the minimum strain reading. Also, the time it took to complete one test was longer than the Turn-of-Nut method and longer than the AICS Specification[9] of ten seconds. The impact wrench had to run longer and often turn the nut farther. Also, the whole procedure took longer since the tightening had to stop, the impact wrench removed, and then the load indicating washer checked with the feeler gage. If the bolt was not tight, the whole procedure had to be repeated.

Another disadvantage is that the Direct Tension Indicator Method #1 is not fool-proof in its effectiveness. It is easy to undermine the verification procedure. An unscrupulous and/or frustrated erector could hit each dimple separately with a hammer and flatten it to the appropriate height. If this washer were installed, an inspector would not be able to notice the tampered washer and could not visually determine if the bolt were tightened properly.

The Direct Tension Indicator Method #1 had the same deficiency as the Turn-of-Nut Method in regards to the increase in final strains for the long bolts. Not all the plates were in full contact at the snug condition. The installation guidelines for the Direct Tension Indicator Method requires that the bolts not be fully tightened at once, but rather they should be all tightened to a certain point and then fully tightened. From these tests it is obvious that the point is greater than "snug" or the full effort of a man on a spud wrench.

The materials for the Direct Tension Indicator Method #1 were more expensive than the Turn-of-Nut method. However, it was cheaper than the Direct Tension Indicator Method #2, which was the most expensive [Table 3].

8.3 Direct Tension Indicator Method #2:

8.3.1 Advantages:

The Direct Tension Indicator Method #2 obviously had a lot of similarities to the Direct Tension Indicator Method #1. The short bolt's strains were adequate for a properly pre-tensioned joint. However, the long bolt's final strains were still a little low.

8.3.2 Disadvantages:

The Direct Tension Indicator Method #2 had some drawbacks. Like Method #1, it took a longer time to tighten the bolt and the entire joint than the Turn-of-Nut method. Also, like the other methods the long bolts had a trend in increased tightness of the final strains. Again this was because the plates were not in full contact at the "snug" condition. Method #2 was the most expensive of all the tightening methods since it required an extra hardened washer in addition to the load indicator washer [Table 3].

9. SUMMARY AND CONCLUSIONS

The results of this study show the following:

1. The Turn-of-Nut method was the most acceptable of all the tested methods for both the long and short bolt lengths. This method was cheapest, easiest, most accurate, and least time consuming of all the methods tested.

2. Direct Tension Indicator Method #1 failed to tighten both the long and short bolts to the minimum standard strain reading, and this makes this method less reliable.

3. The Direct Tension Indicator Method #2 failed to tighten the long bolts to minimum pre-tension, but did succeed in tightening the short ones to the minimum pre-tension.

4. The tightening procedure is unaffected by the orientation of the bolt. Bolts installed in vertical and horizontal test assemblies yielded similar results.

5. The bolt length was by far the most influential factor in the tightening process. In all methods the short bolts' final strains were significantly higher than the long bolts.

6. The condition of the threads whether greased or oiled had a slightly significant effect on the bolts of the Turn-of-Nut method. It did not seem to affect the bolts tightened by the Direct Indicator Method.

7. More testing should be done to determine a new maximum rotation for the short bolts. The specified one third turn is large and results in a high strain for the short A490 1¼ inch diameter bolts. These strains are not high enough for the bolts to fail inspection. However, a lower strain would be more efficient.

8. The time to tighten each bolt is longer than the AISC Specification[9] of ten seconds, even after using the largest impact wrenches available. The tightening times for the Direct Tension Indicator Methods #1 and #2 were longer than the J & M Turner's recommended time of twenty seconds.

9. The snug condition did not bring all the plates into contact when there were a large number of plates. Since the plates were not in full contact, there was a rise in final strains as the joint was tightened.

10. Both the Cleco W-2119 and the CP-614 were capable of tightening the A490 1¼ inch bolts when they were in proper working order. The new Cleco W-2119 did work faster than the CP-614.

TABLE 1: TEST PROGRAM AND VARIABLES

Turn-of-Nut Method

Test Name	Bolt Length Long	Bolt Length Short	Thread Condition Greased	Thread Condition Oiled	Orientation Vertical	Orientation Horizontal
T-LGV	X		X		X	
T-LGH	X		X			X
T-LOV	X			X	X	
T-LOH	X			X		X
T-SGV		X	X		X	
T-SGH		X	X			X
T-SOV		X		X	X	
T-SOH		X		X		X

Direct Tension Indicator Method #1

Test Name	Bolt Length Long	Bolt Length Short	Thread Condition Greased	Thread Condition Oiled	Orientation Vertical	Orientation Horizontal
D1-LGV	X		X		X	
D1-LGH	X		X			X
D1-LOV	X			X	X	
D1-LOH	X			X		X
D1-SGV		X	X		X	
D1-SGH		X	X			X
D1-SOV		X		X	X	
D1-SOH		X		X		X

Direct Tension Indicator Method #2

Test Name	Bolt Length Long	Bolt Length Short	Thread Condition Greased	Thread Condition Oiled	Orientation Vertical	Orientation Horizontal
D2-LGV2	X		X		X	
D2-SGV2		X	X		X	

TABLE 2: OPERATION TIMES AND AVERAGE FINAL STRAIN READINGS

Test	Time per bolt (seconds)	Total test time (minutes)	Average Final Strains** ($x 10^{-6}$)
T-LGH	29	31	2622
D1-LGH	52	55	2132
T-LGV	38	32	2496
D1-LGV	50	53	2108
D2-LGV2	36	54	2457
T-LOH	22	36	2444
T-LOV	13	29	2012
D1-LOV	50	51	1819
T-SGH*	37	32	3886
D1-SGH	30	55	2374
T-SGV	17	30	3198
D1-SGV	37	57	2299
D2-SGV2	34	42	2765
T-SOH	16	23	2905
D1-SOH	36	53	2014
T-SOV	19	25	2829
D1-SOV	26	32	2541

* First test: procedure was being developed, therefore slower than other tests.

** 2500×10^{-6} is the minimal acceptable final strain reading.

TABLE 3: COST* COMPARISON OF BOLT ASSEMBLIES

	Long Bolt	Short Bolt
Turn-of-Nut Method		
Bolt	$17.50	$7.80
2 Hardened Washers	4.98	4.98
Total	22.48	12.78
Direct Tension Indicator Method #1		
Bolt	$17.50	$7.80
2 Hardened Washers	4.98	4.98
Load Indicating Washer	4.20	4.20
Total	26.68	16.98
Direct Tension Indicator Method #2		
Bolt	$17.50	$7.80
3 Hardened Washers	7.47	7.47
Load Indicating Washer	4.20	4.20
Total	29.17	19.47
Cost Differences		
Method #1 (Amount)	$4.20	$4.20
(Percent Higher)	18%	32%
Method #2 (Amount)	$6.69	$6.69
(Percent Higher)	29%	52%

* Cost for materials only

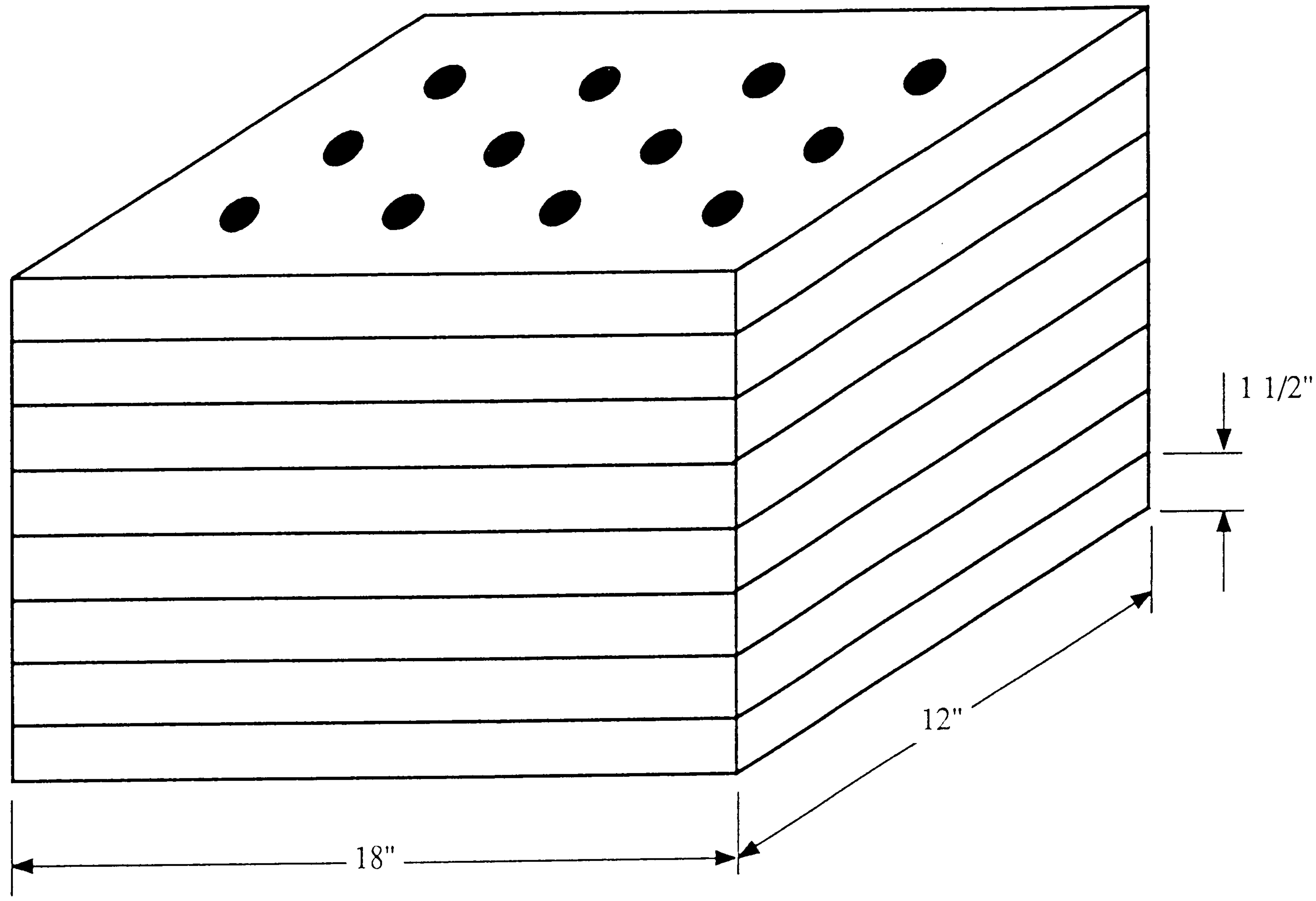


FIGURE 1: PLATE SETUP FOR LONG BOLTS

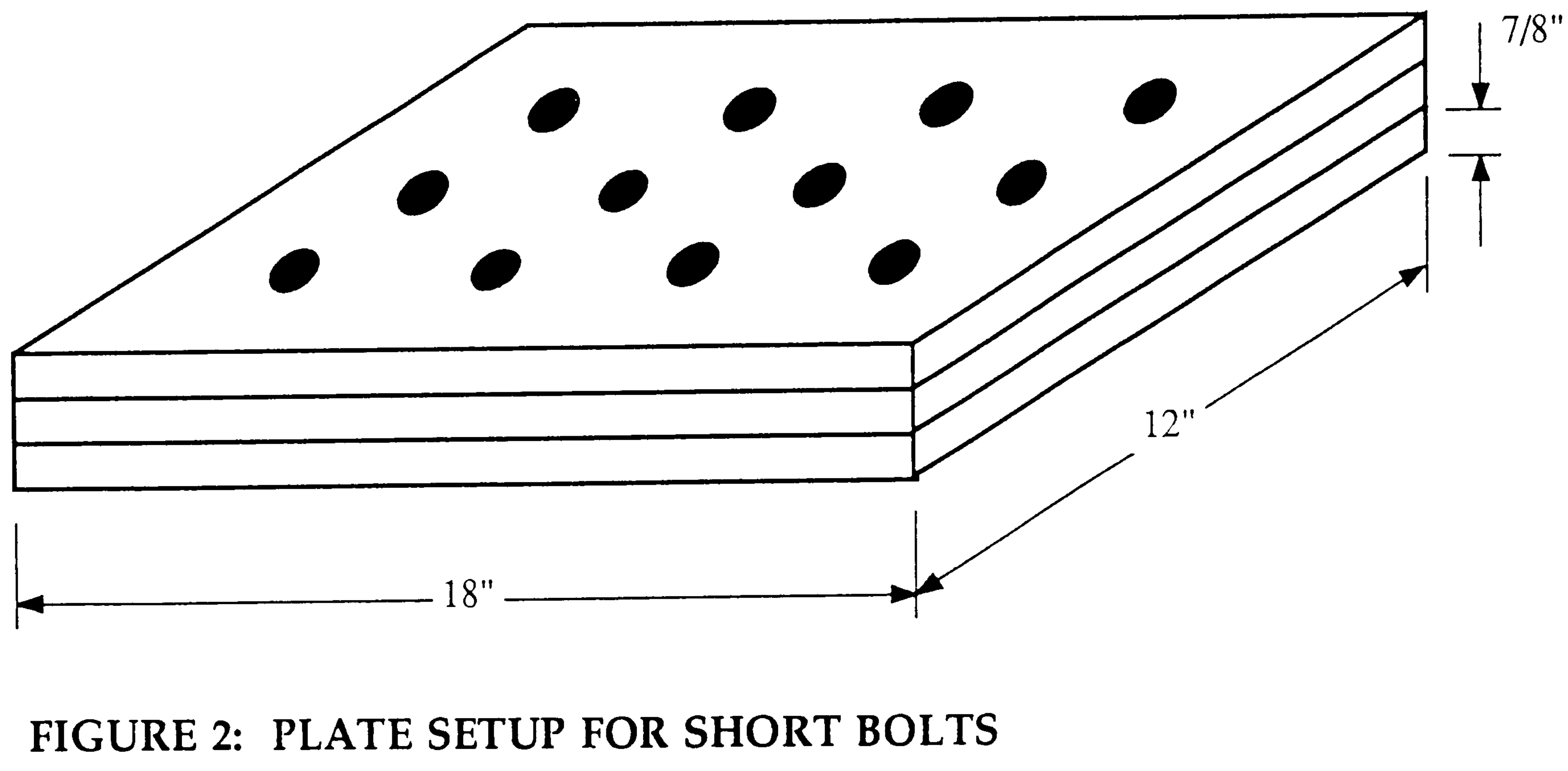
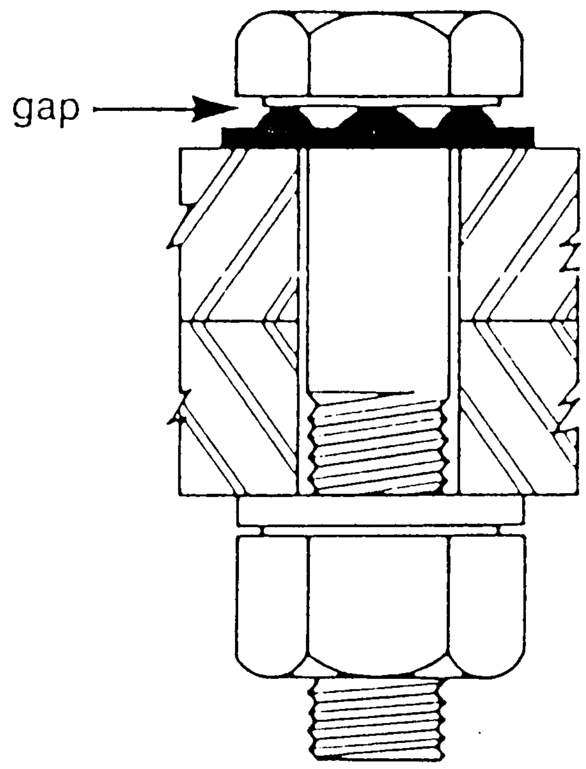
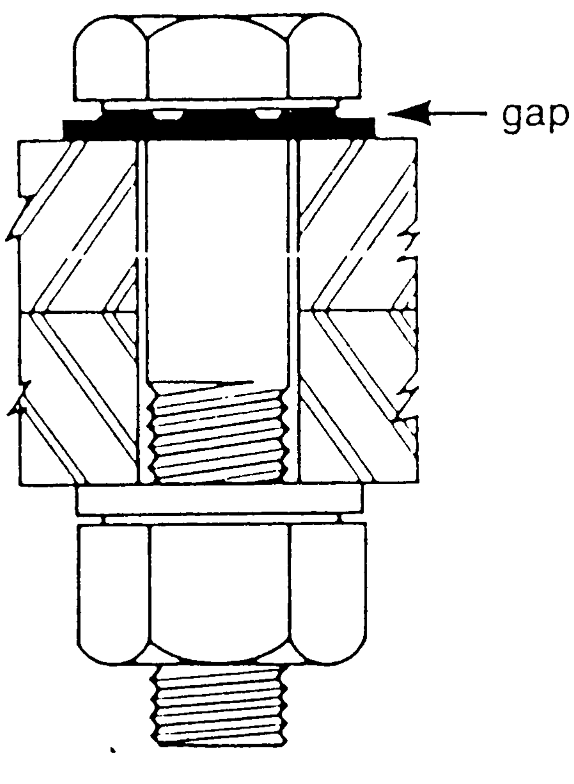


FIGURE 2: PLATE SETUP FOR SHORT BOLTS



INITIAL



AFTER TIGHTENING

FIGURE 3: DIRECT TENSION INDICATOR METHOD #1

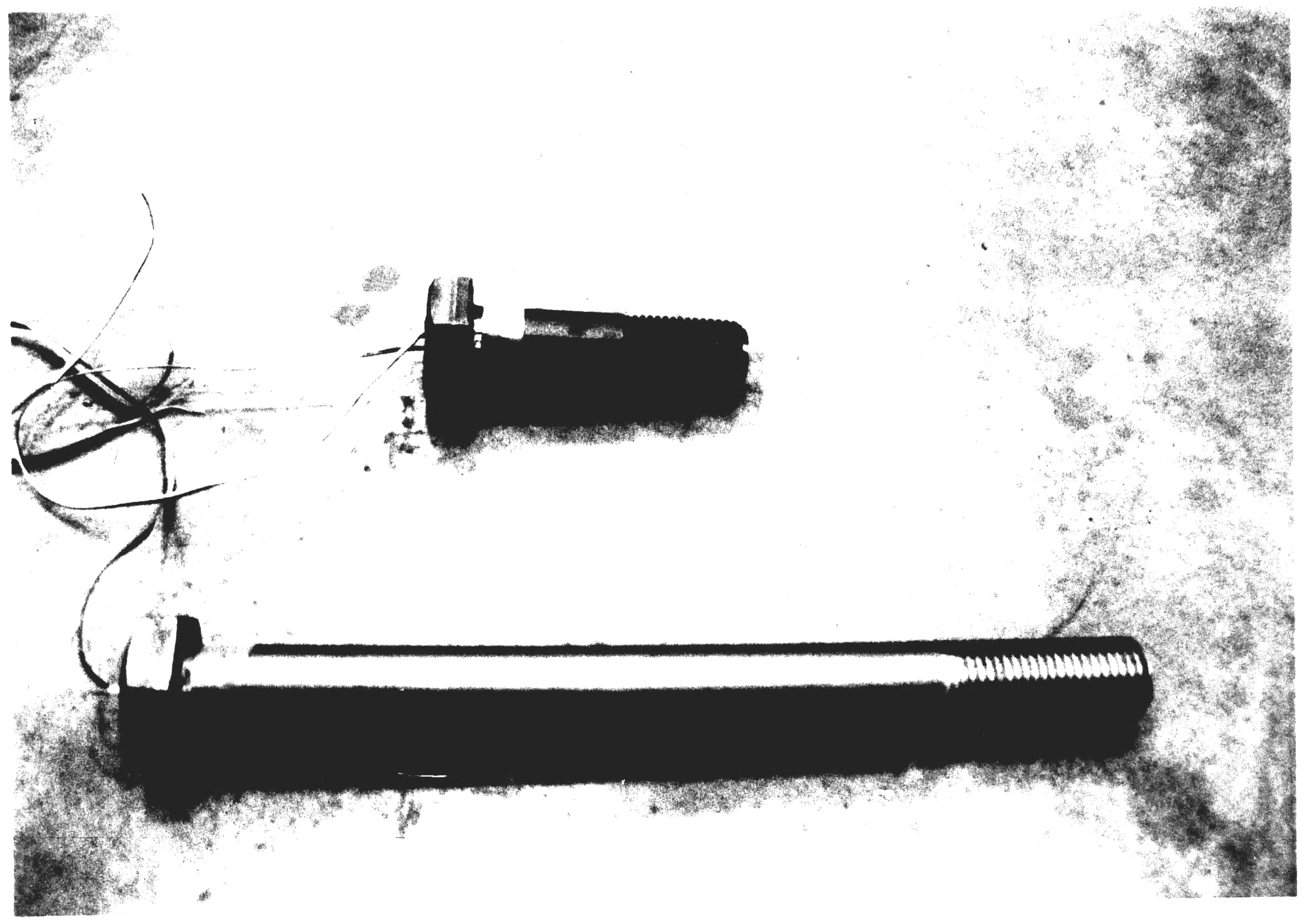


FIGURE 4: A490 1¼ INCH BOLTS USED IN PROGRAM

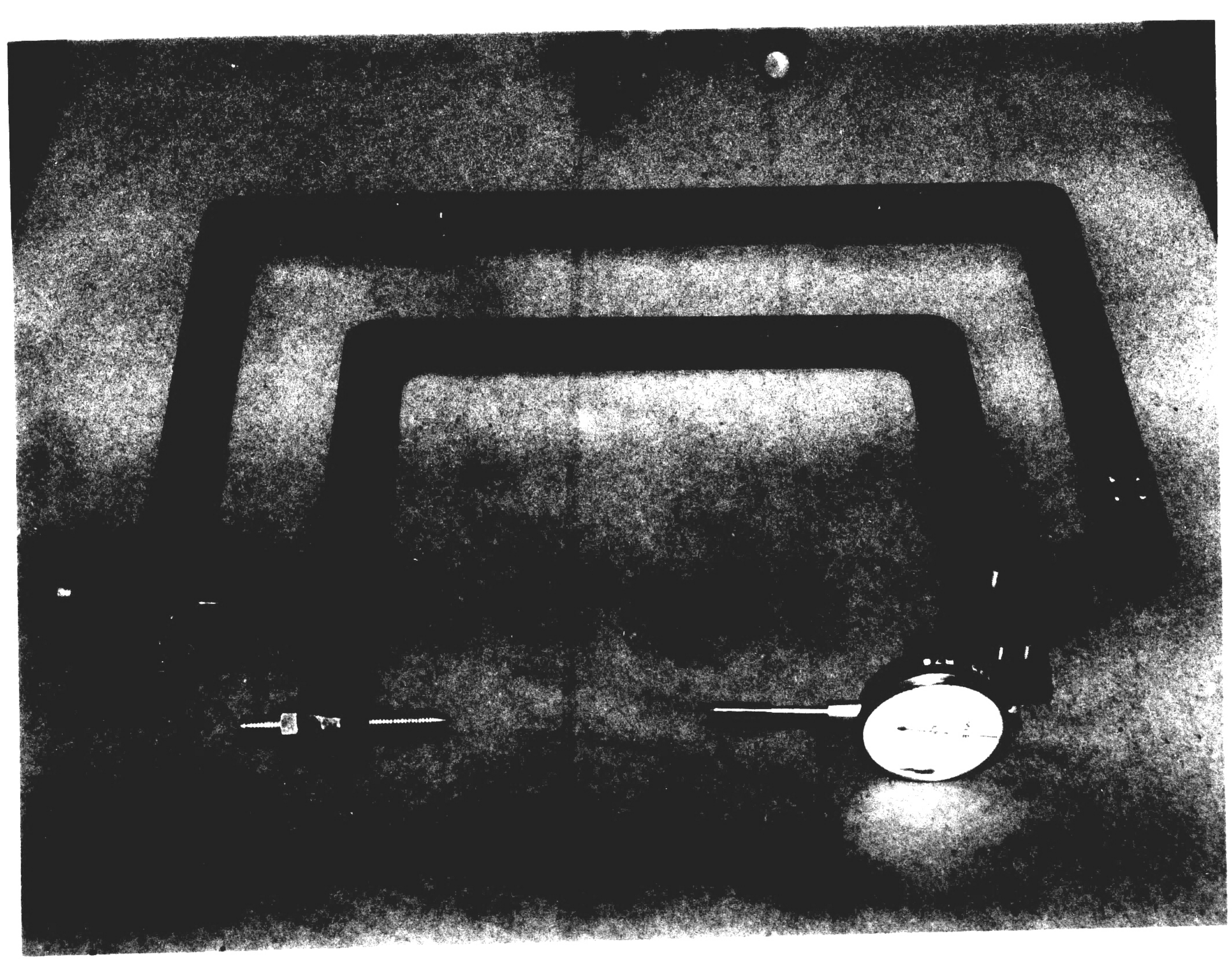


FIGURE 5: C-CLAMP DIAL GAGE

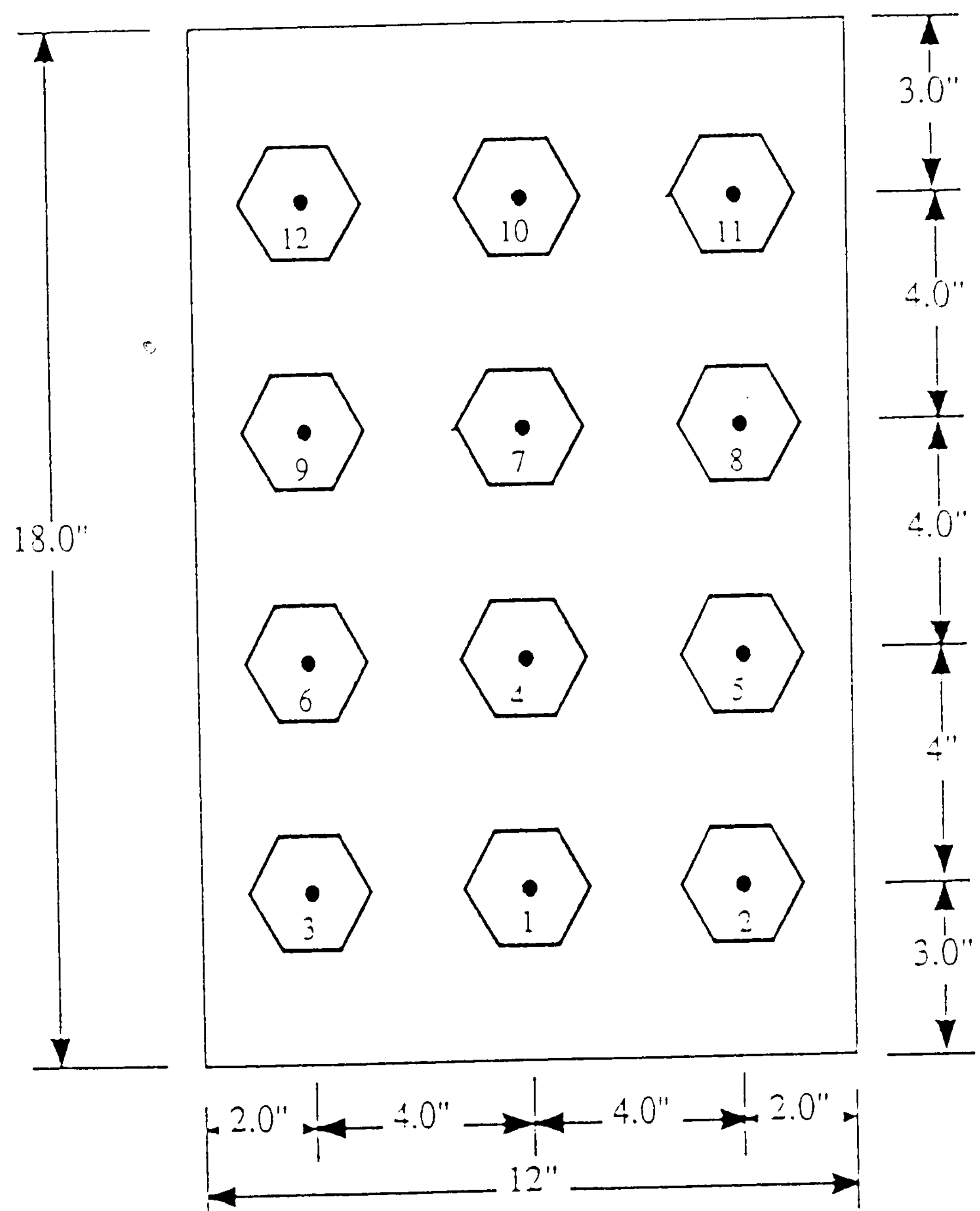


FIGURE 6: BOLT TIGHTENING SEQUENCE FOR VERTICAL PLATES

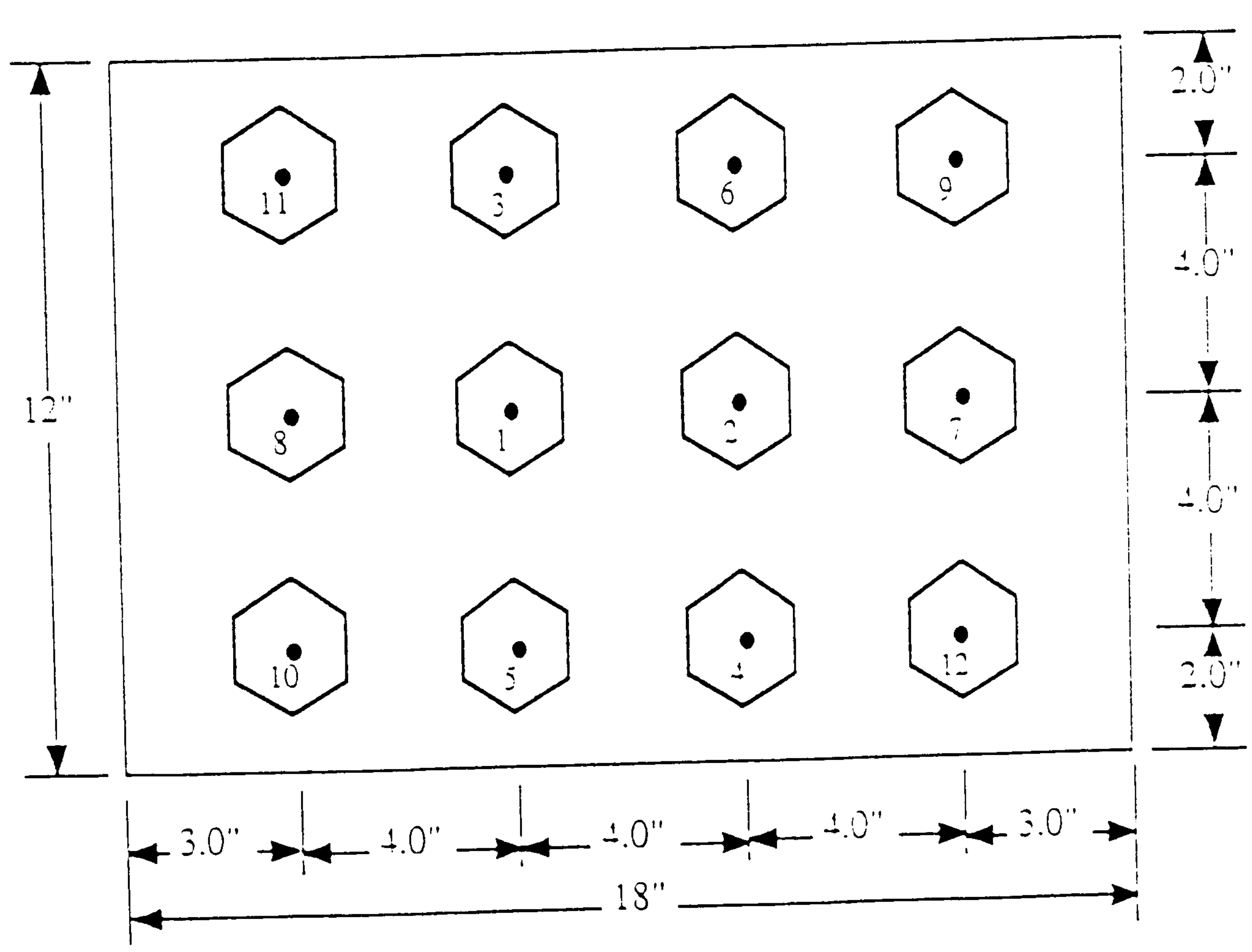


FIGURE 7: BOLT TIGHTENING SEQUENCE FOR HORIZONTAL PLATES

FIGURE 8: VERTICAL A36 STEEL PLATE SET UP

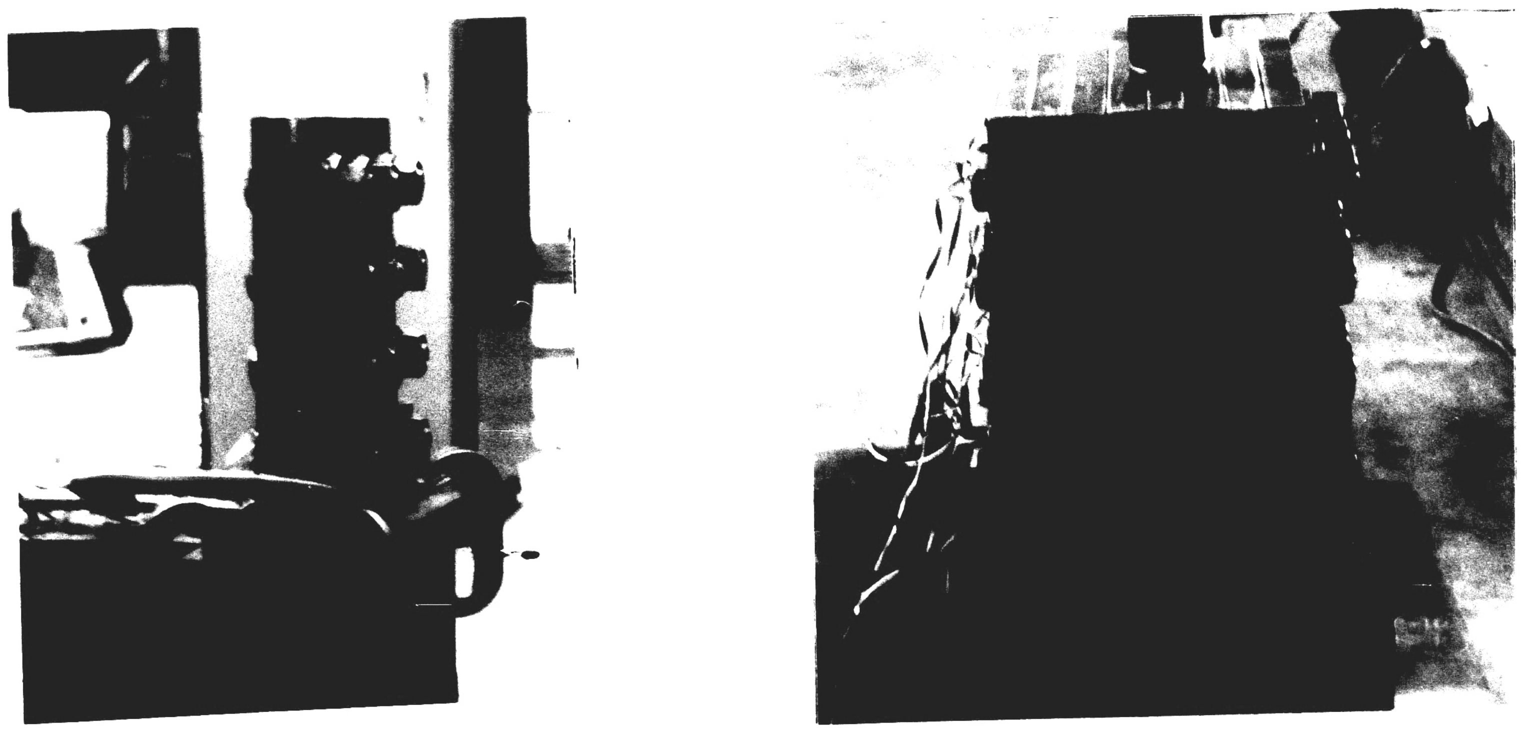


FIGURE 9: SHORT AND LONG BOLT VERTICAL SET UP

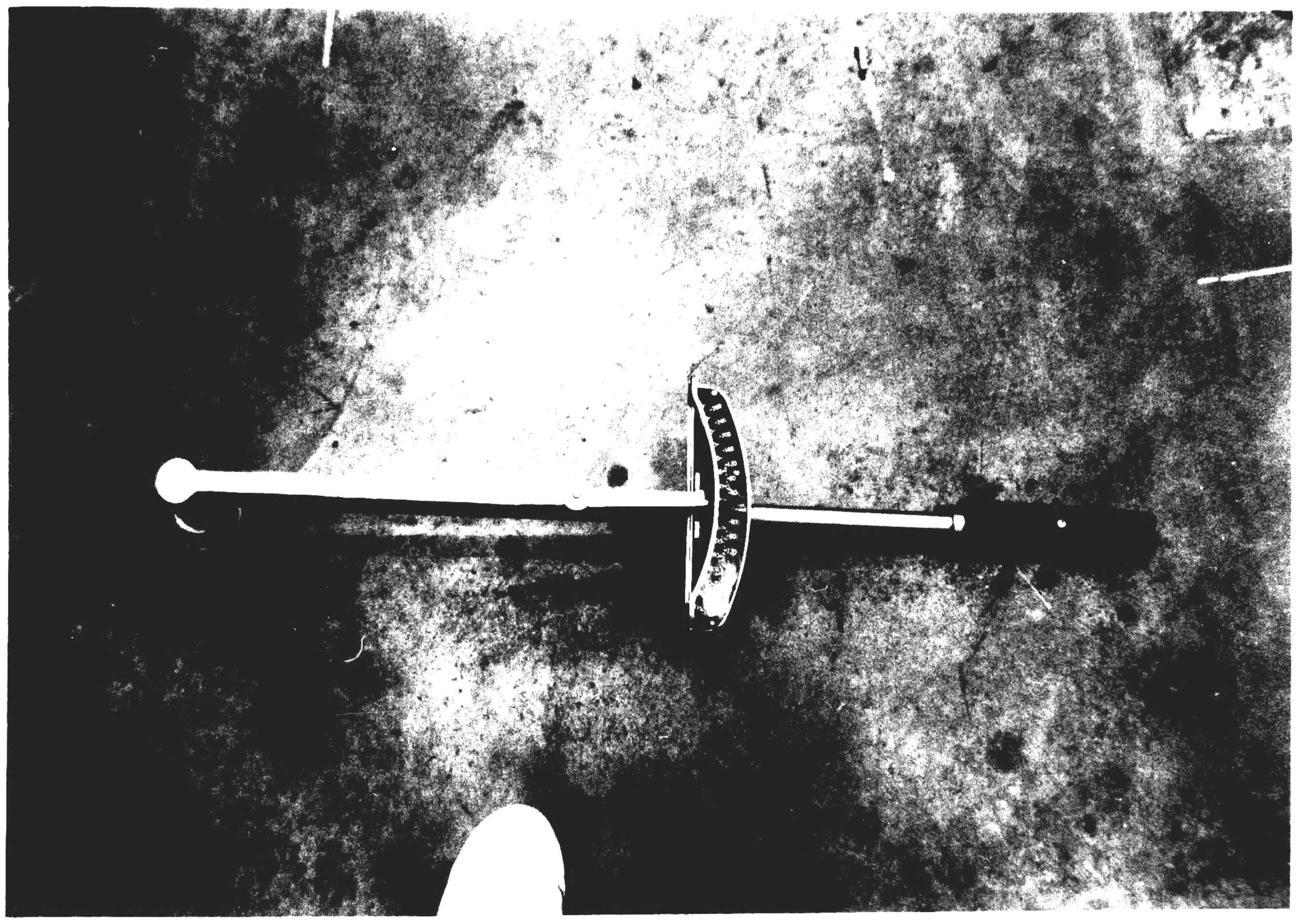
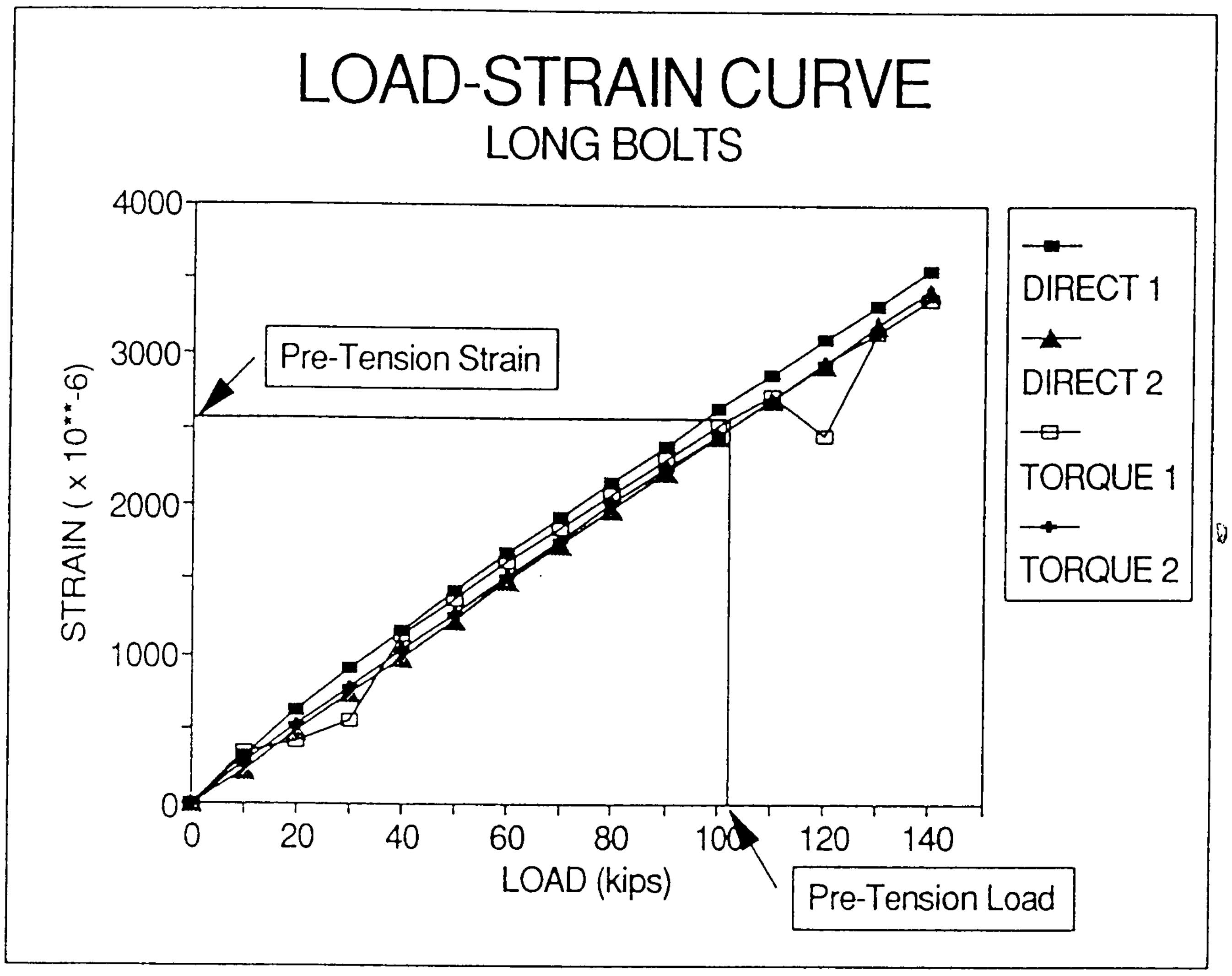


FIGURE 10: CALIBRATED TORQUE WRENCH



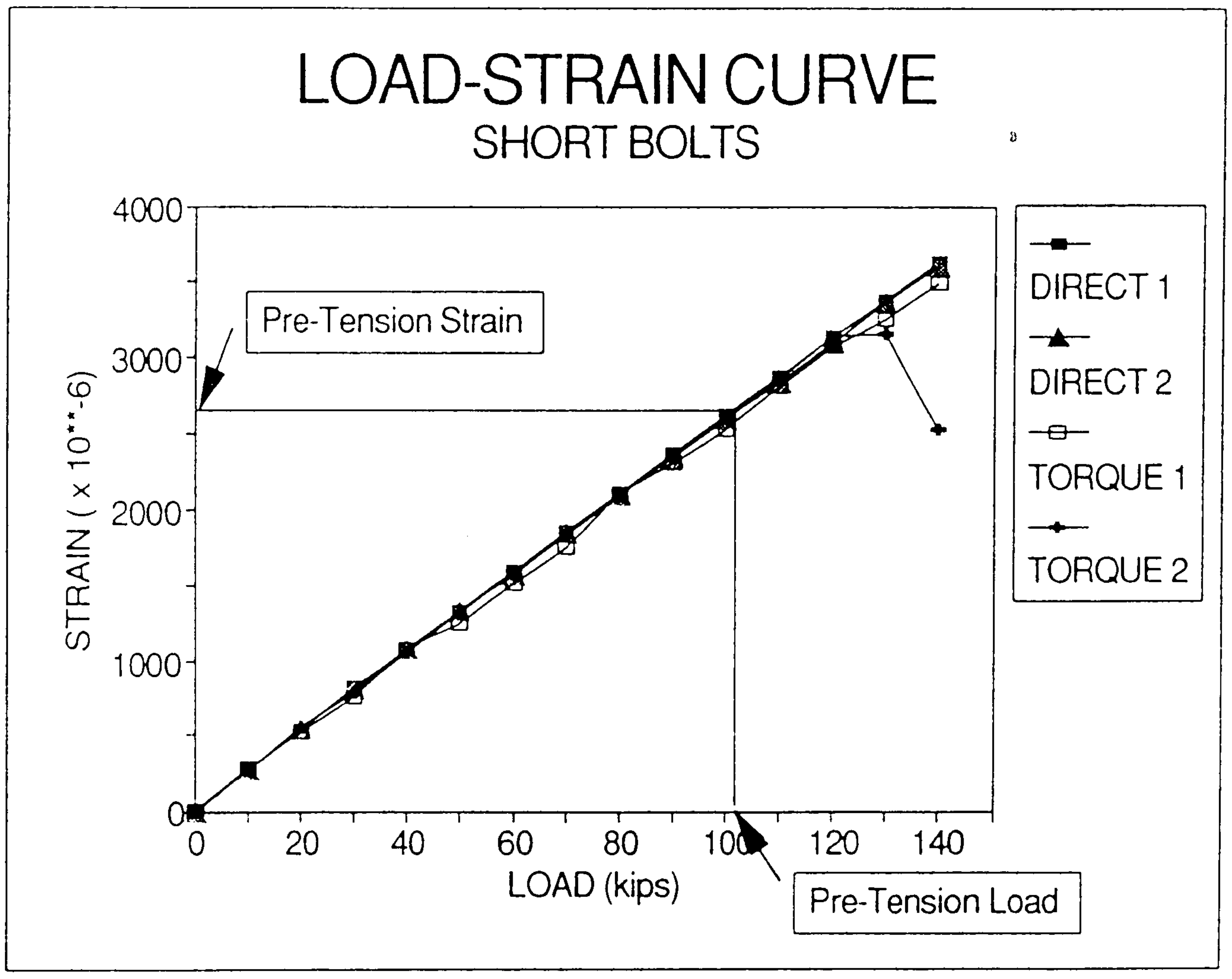


FIGURE 11: LOAD-STRAIN CURVES

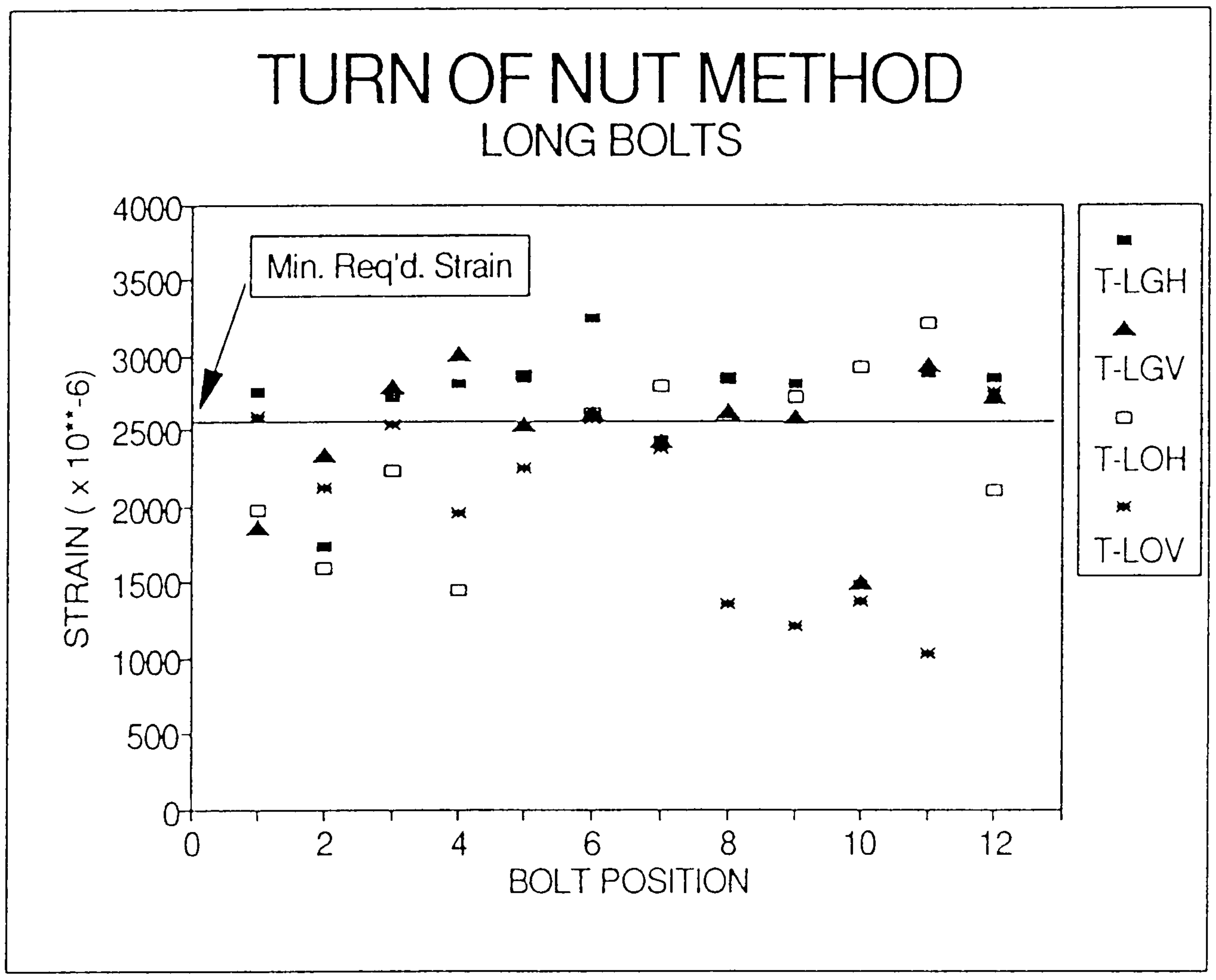


FIGURE 12: TURN-OF-NUT METHOD...LONG BOLTS

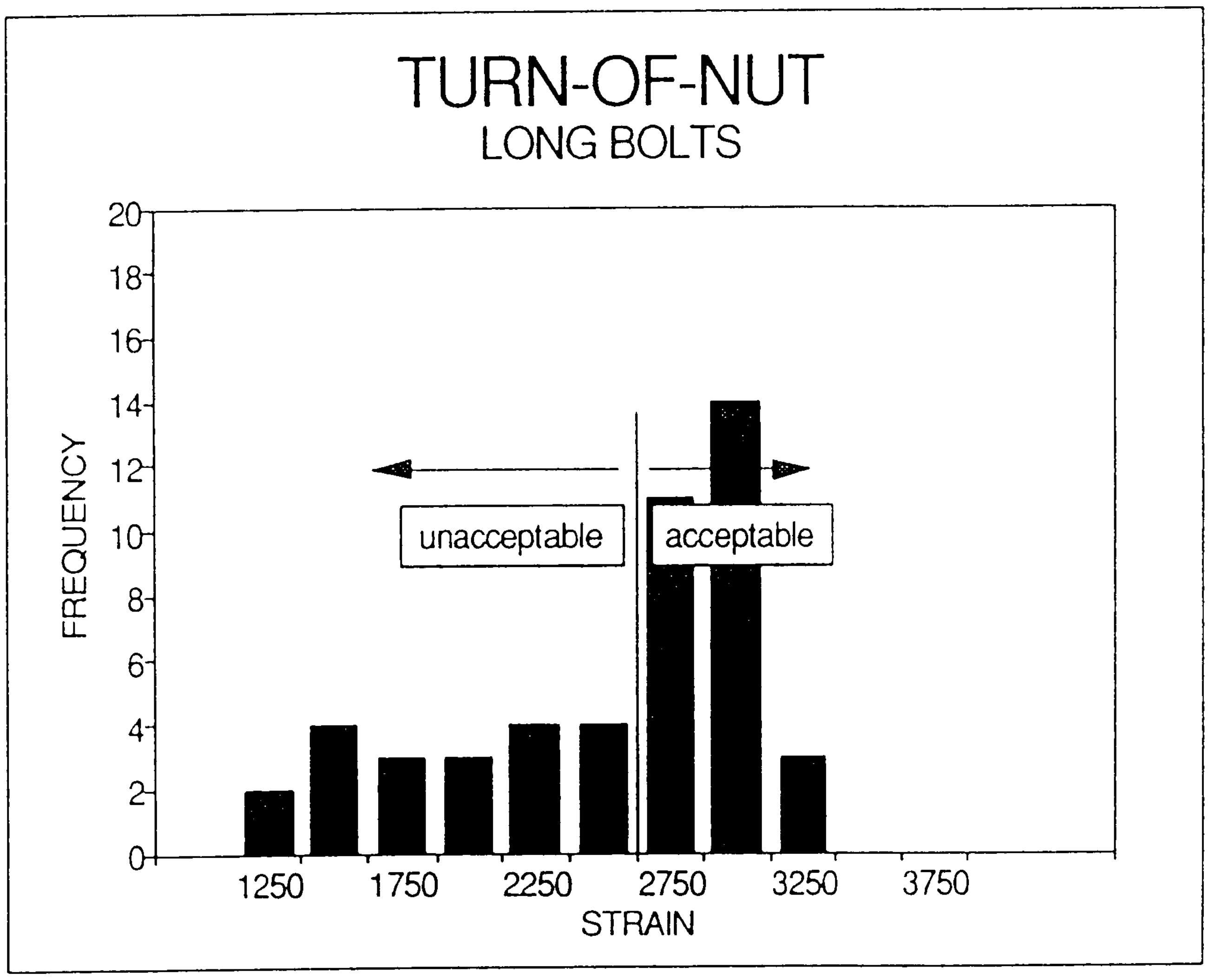


FIGURE 13: FREQUENCY DIAGRAM FOR TURN-OF-NUT METHOD... LONG BOLTS

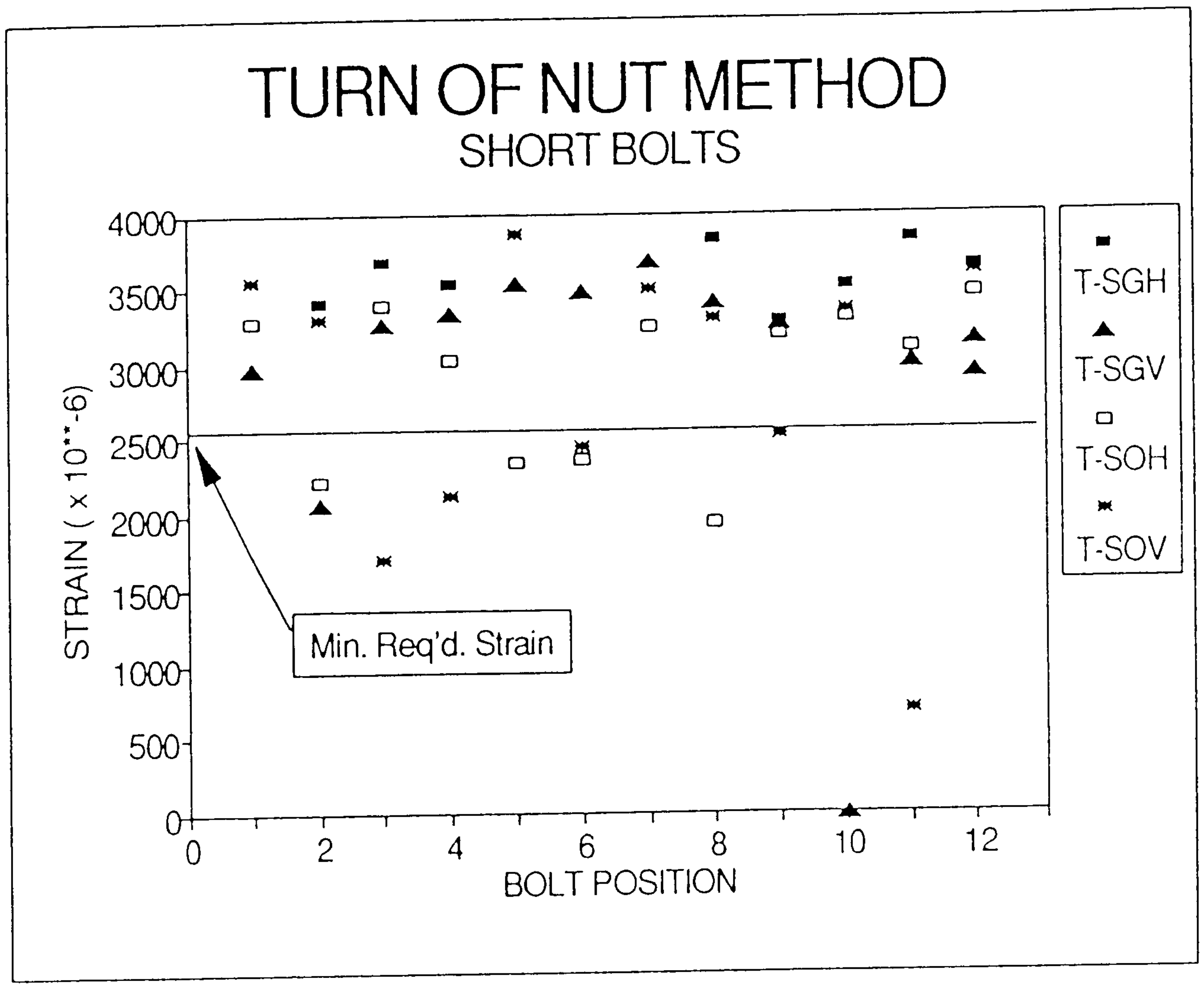


FIGURE 14: TURN-OF-NUT METHOD...SHORT BOLTS

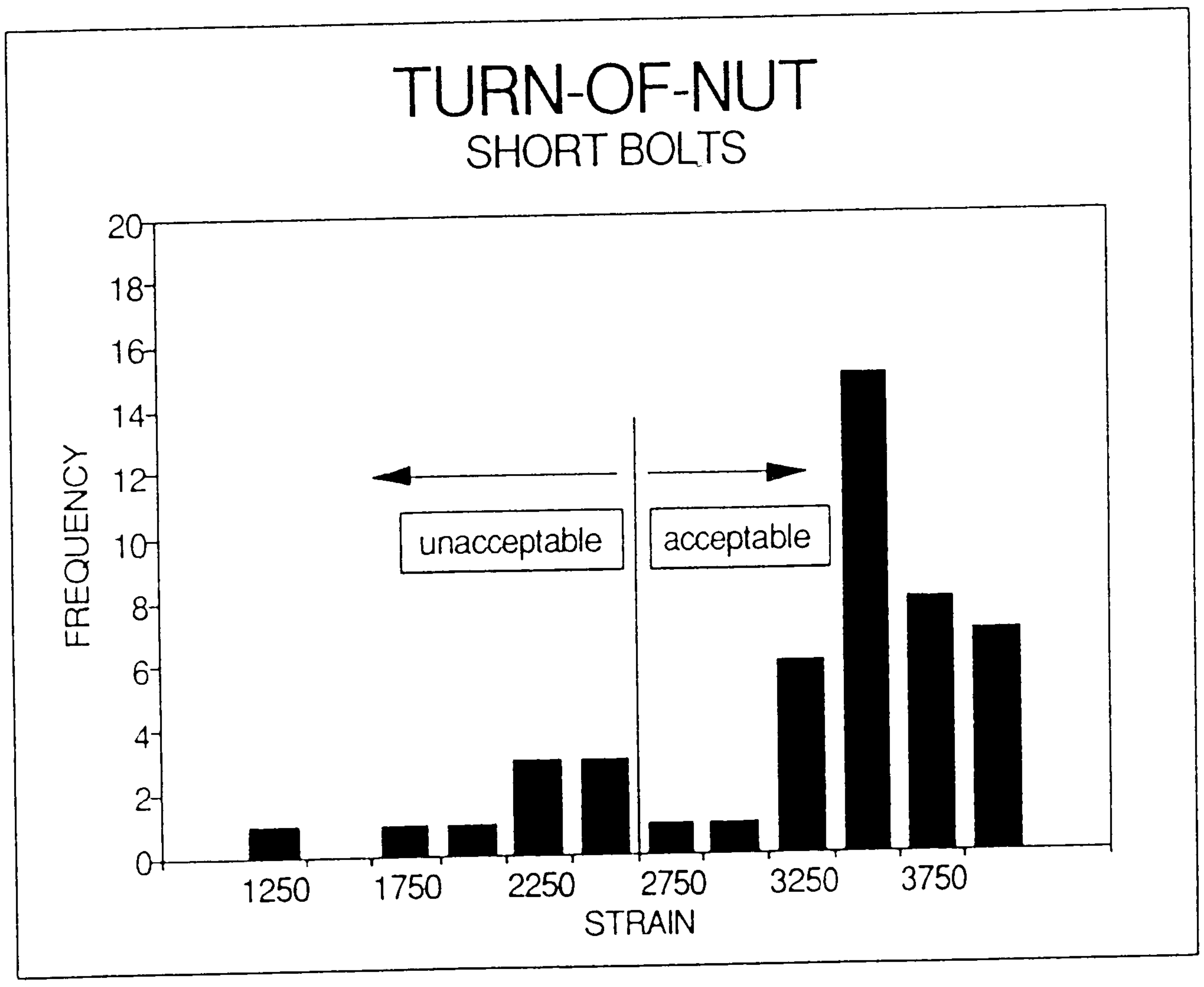


FIGURE 15: FREQUENCY DIAGRAM FOR TURN-OF-NUT METHOD ...SHORT BOLTS

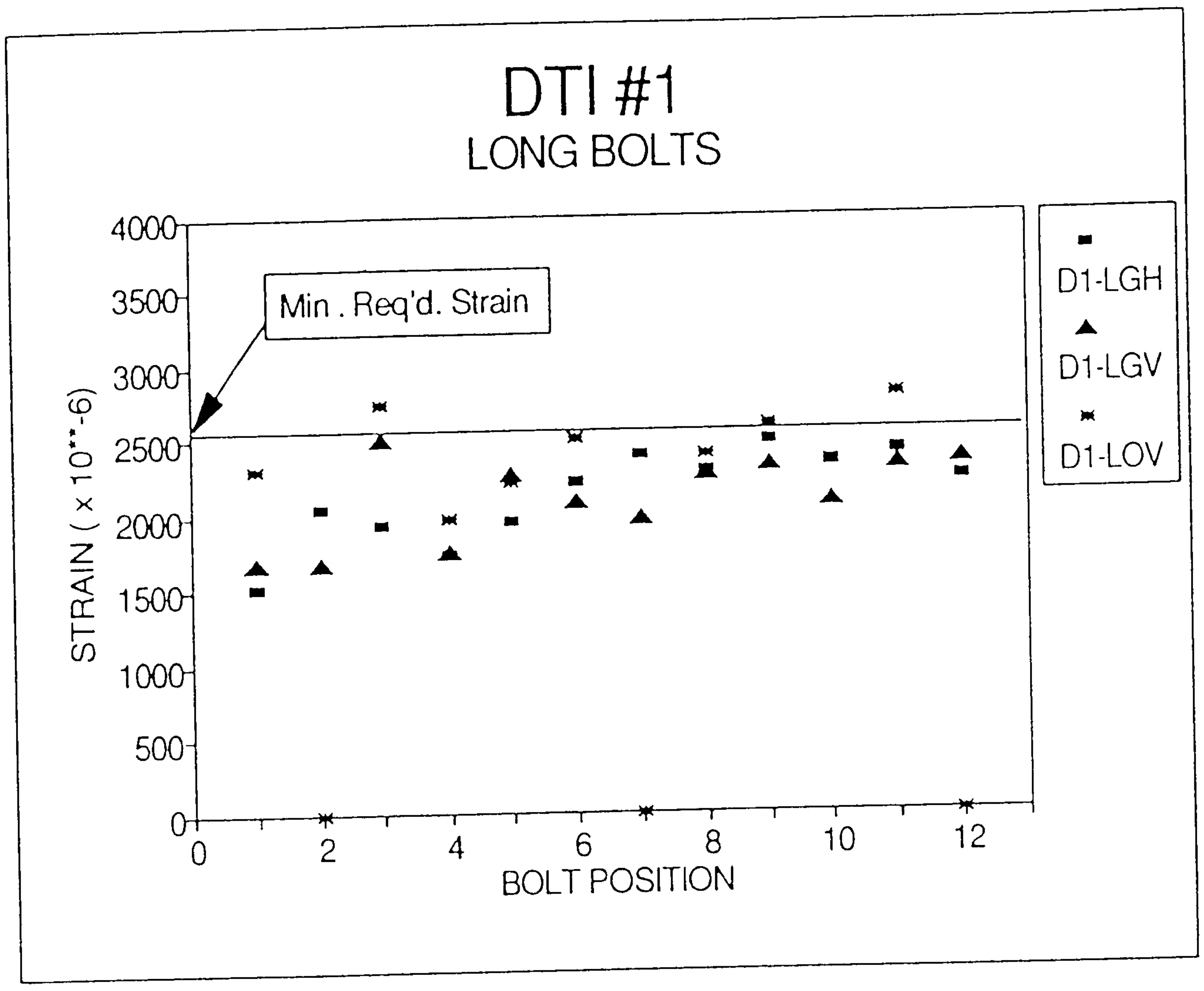


FIGURE 16: DIRECT TENSION INDICATOR METHOD #1...LONG BOLTS

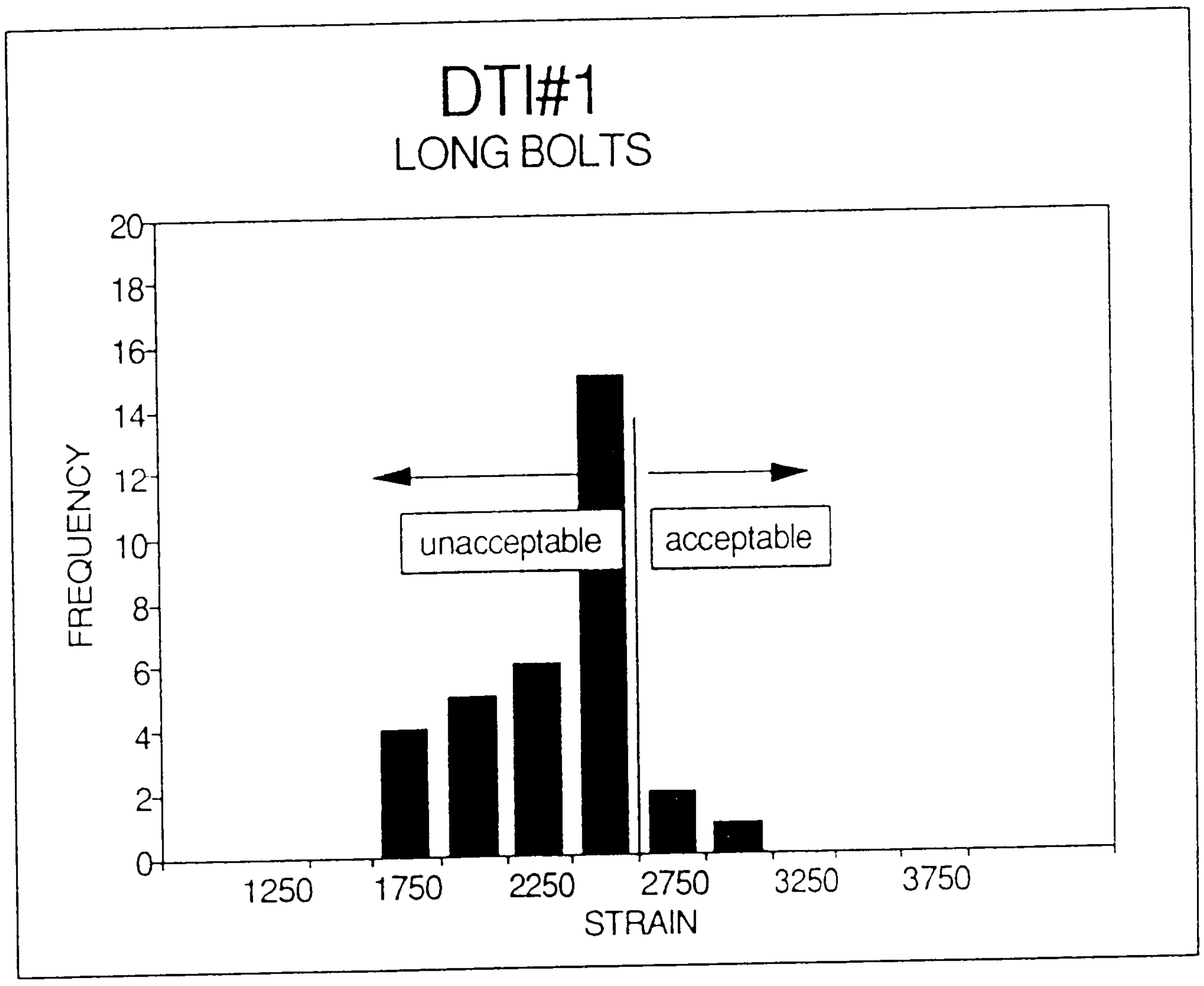


FIGURE 17: FREQUENCY DIAGRAM FOR DIRECT TENSION INDICATOR METHOD #1...LONG BOLTS

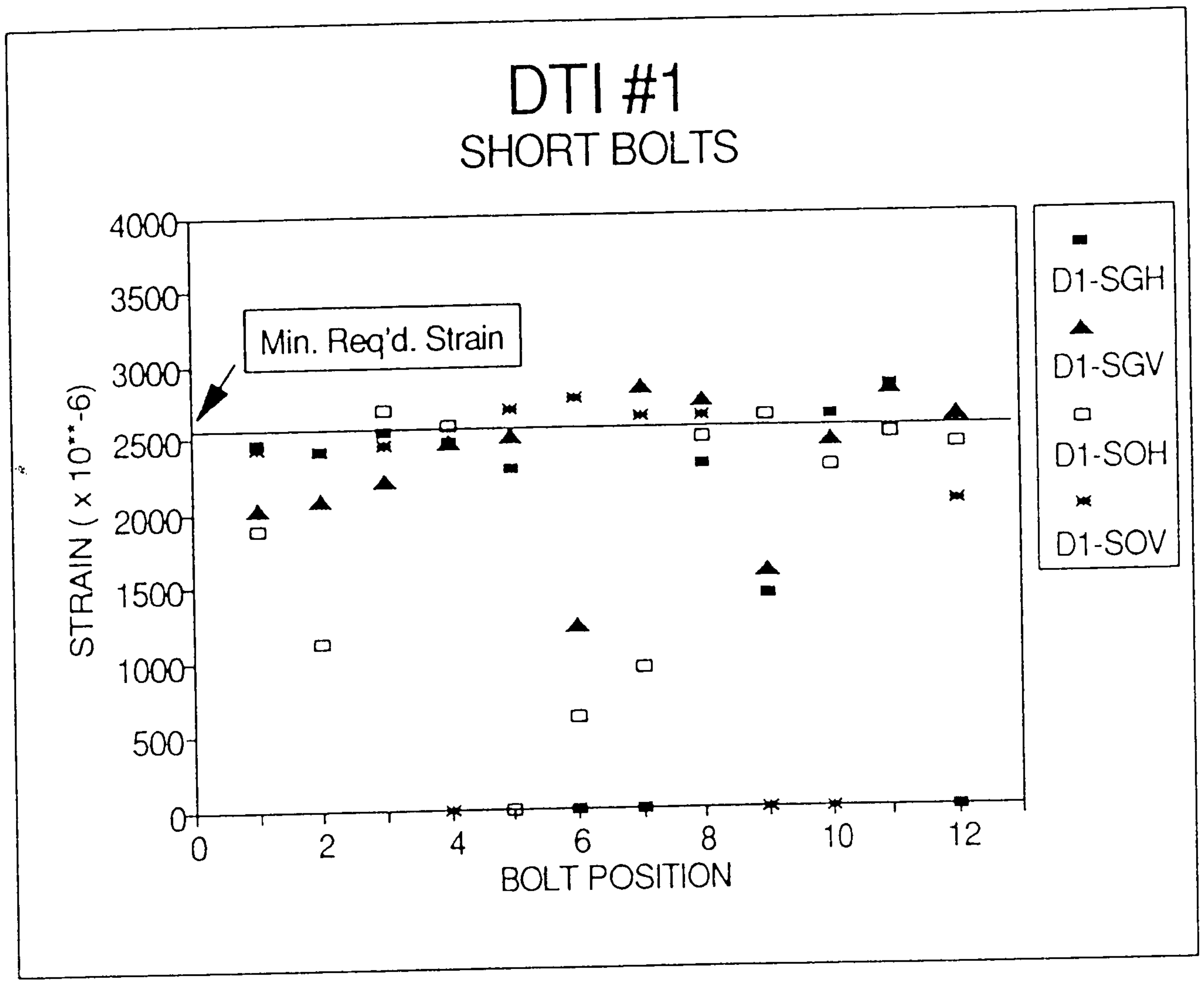


FIGURE 18: DIRECT TENSION INDICATOR METHOD #1...SHORT BOLTS

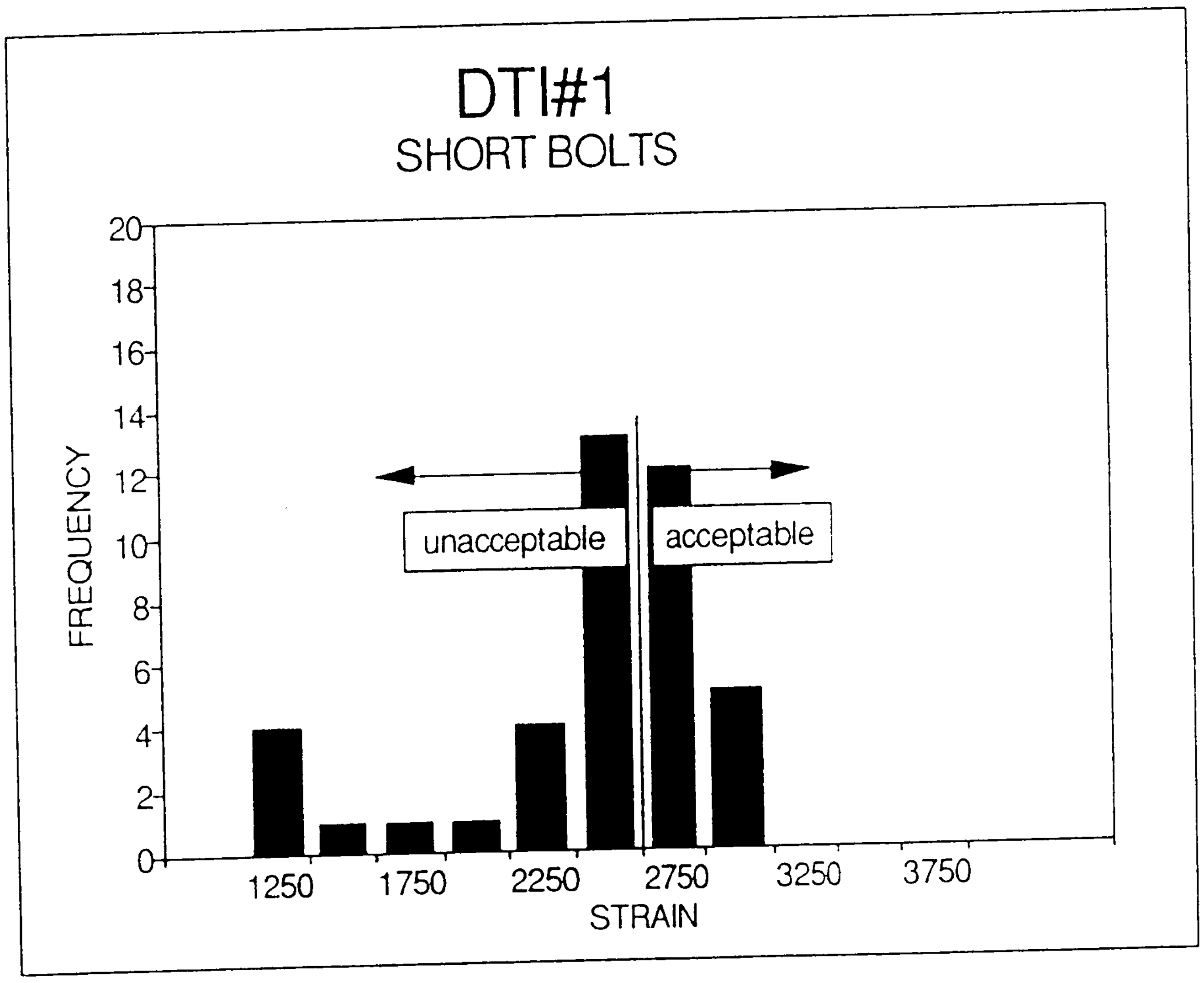


FIGURE 19: FREQUENCY DIAGRAM FOR DIRECT TENSION INDICATOR METHOD #1...SHORT BOLTS

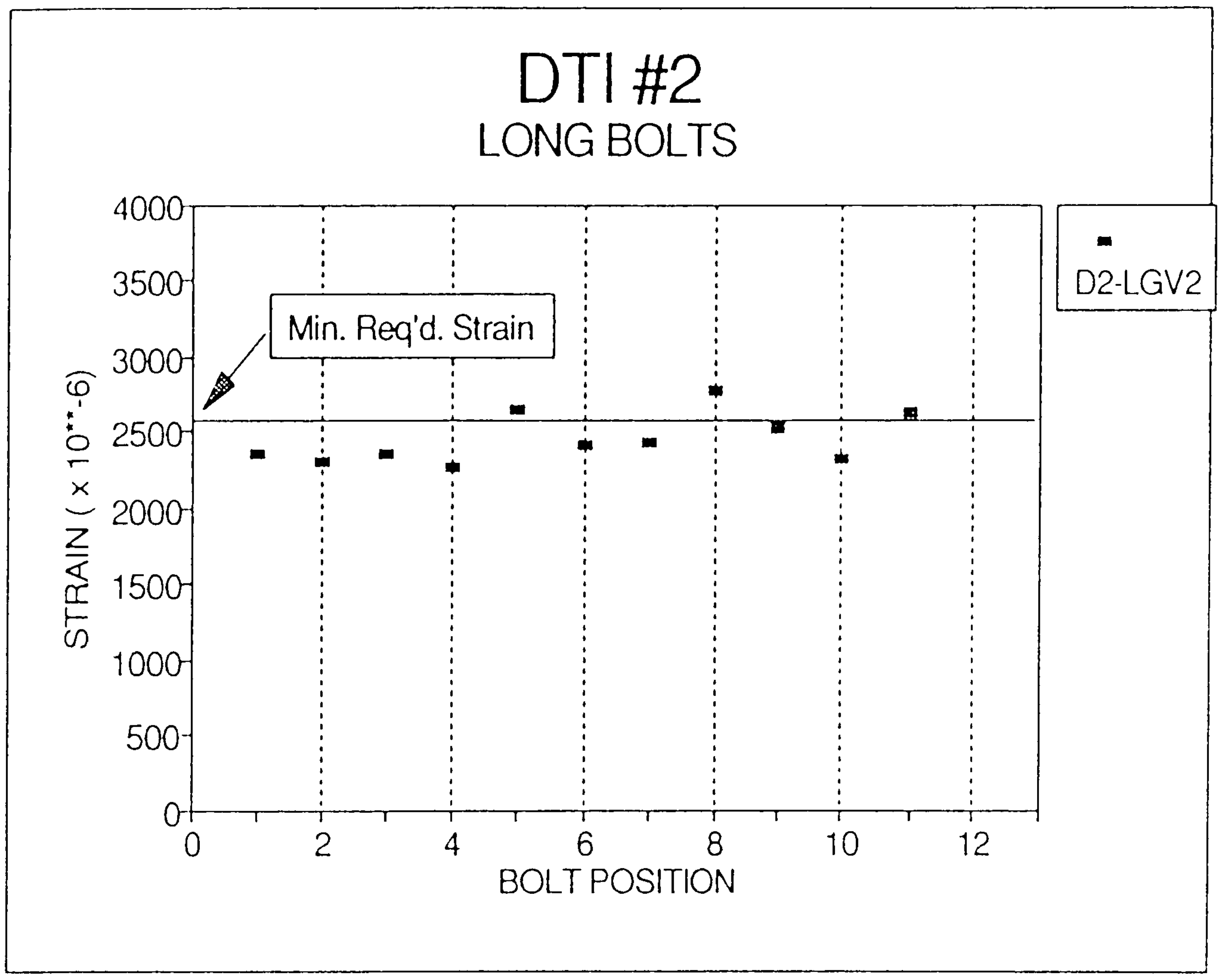


FIGURE 20: DIRECT TENSION INDICATOR METHOD #2...LONG BOLTS

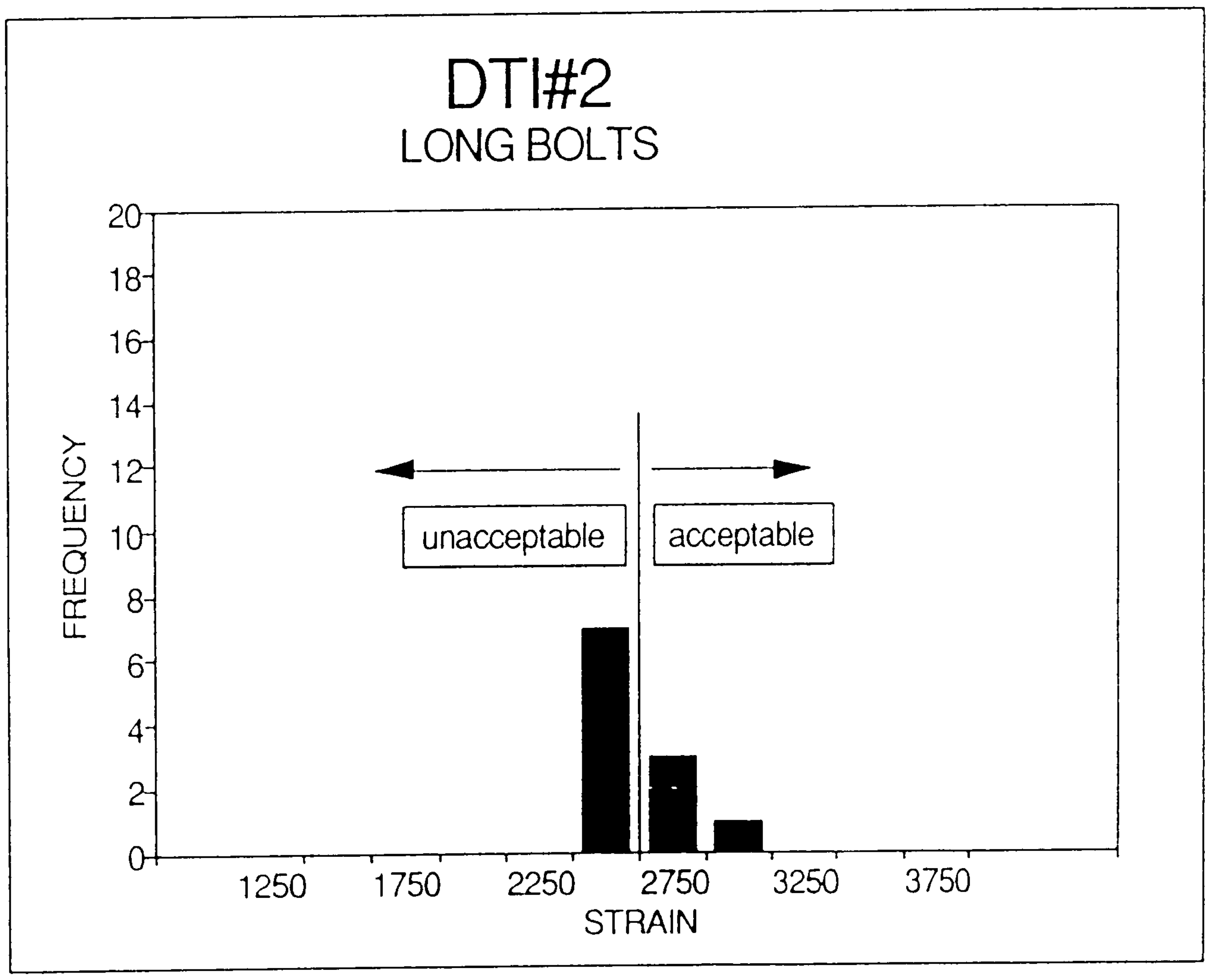


FIGURE 21: FREQUENCY DIAGRAM FOR DIRECT TENSION INDICATOR METHOD #2...LONG BOLTS

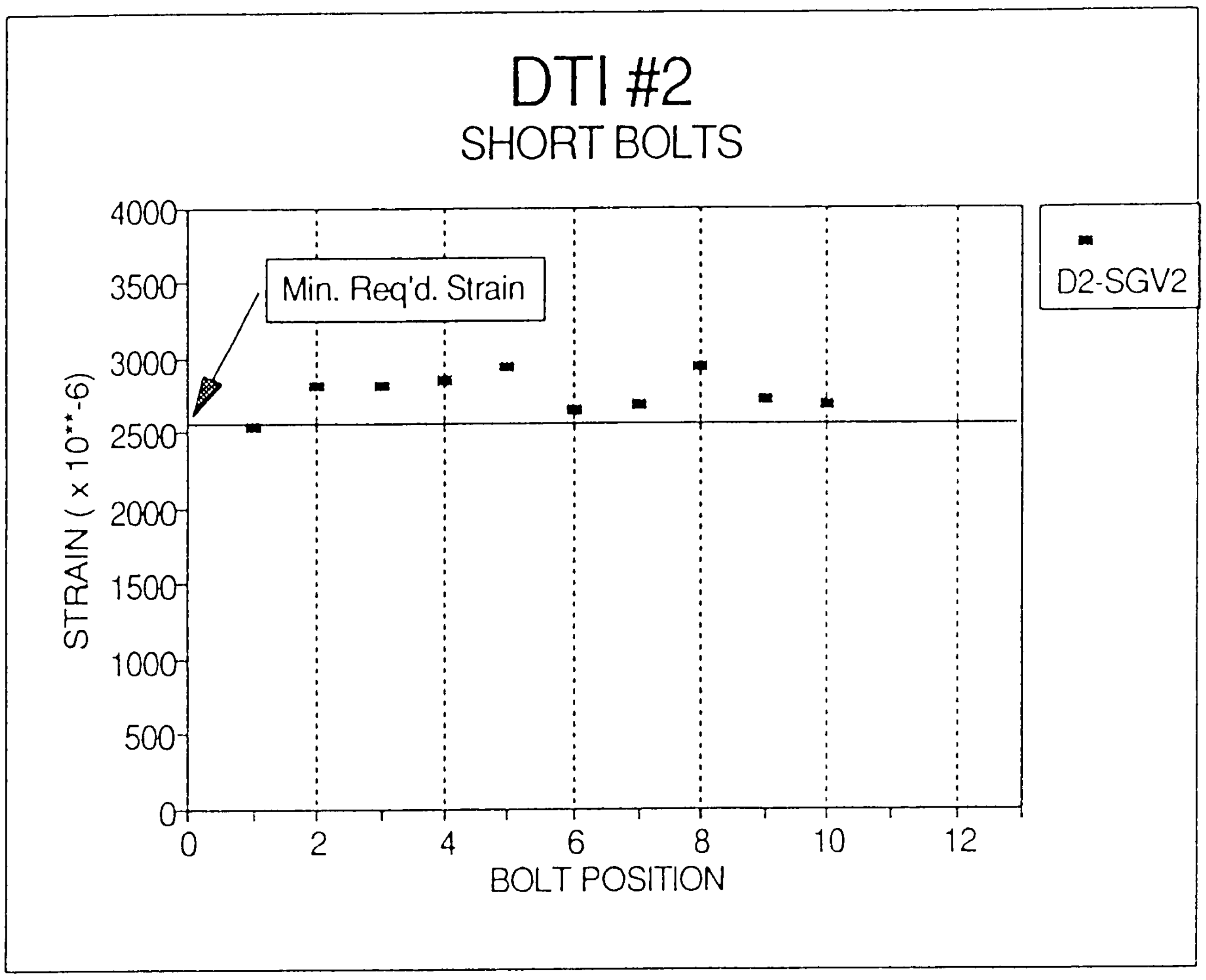


FIGURE 22: DIRECT TENSION INDICATOR METHOD #2...SHORT BOLTS

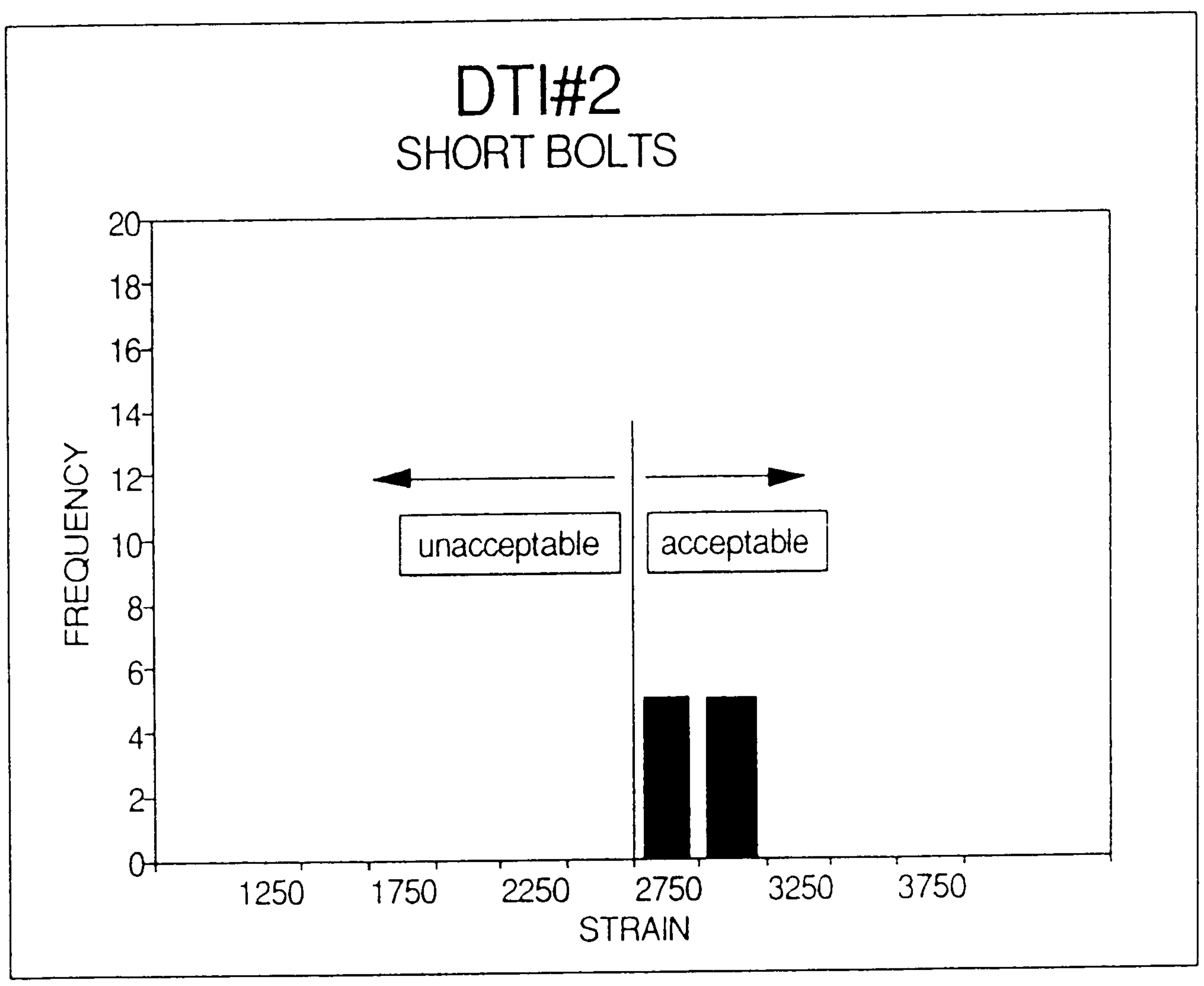


FIGURE 23: FREQUENCY DIAGRAM FOR DIRECT TENSION INDICATOR METHOD #2...SHORT BOLTS

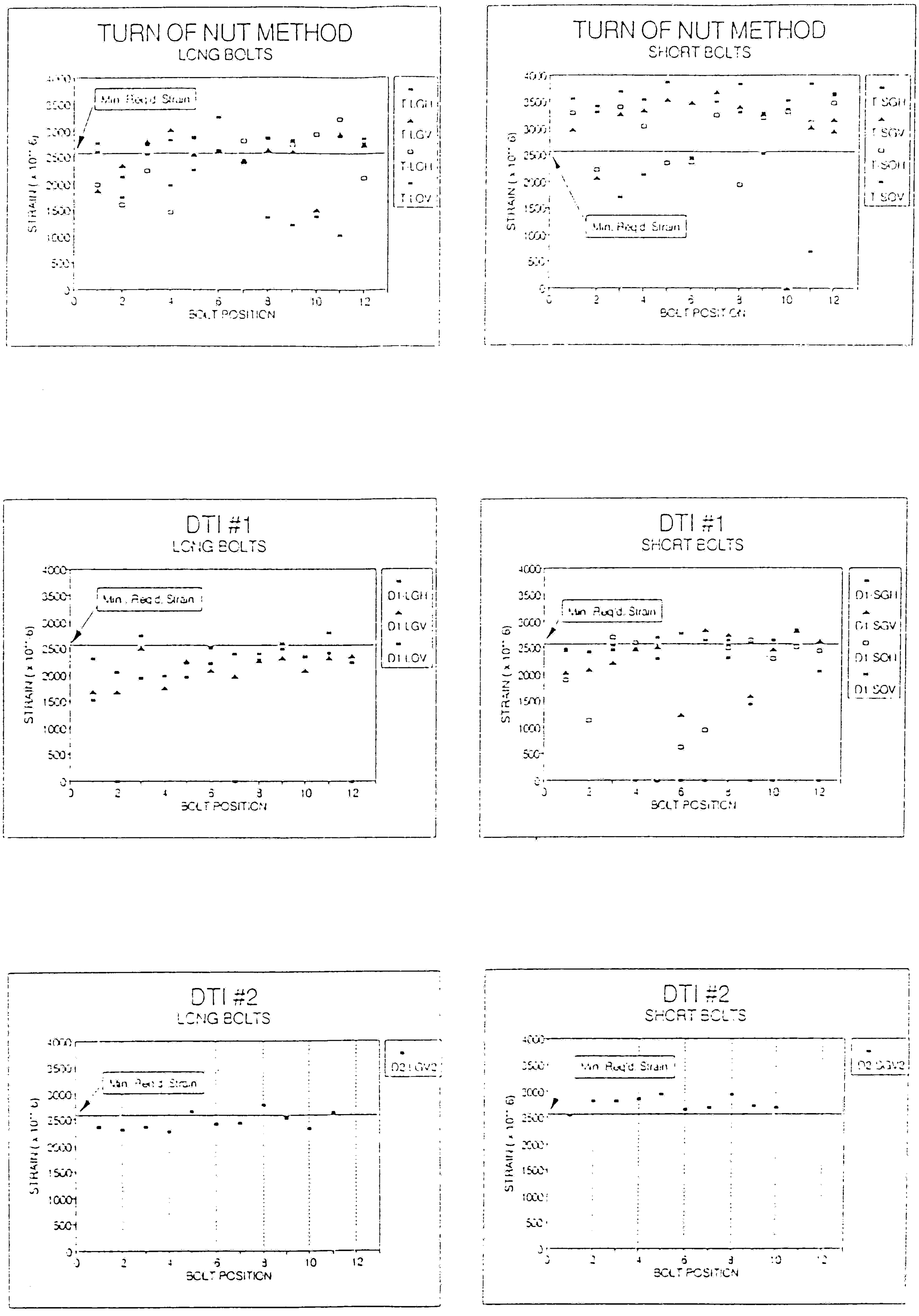


FIGURE 18: ALL TIGHTENING METHODS

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VITA

The author was born in Williamsport, Pennsylvania on October 31, 1963, as the second child of Ingrid and Kent Dahl. She graduated from Lewistown Area High School in 1981 and went on to study at Carnegie Mellon University in Pittsburgh, Pennsylvania. She graduated from college in 1985 with a Bachelor of Science Degree in Civil Engineering.

After graduating, the author was commissioned as a Second Lieutenant into the Corps of Engineers in the United States Army. She was in a number of leadership and staff positions to include Platoon Leader for a vertical construction platoon and a heavy construction platoon, as well as the battalion Construction Officer for the 249th Engineer Combat Battalion (Heavy) in Karlsruhe, Germany.

The author entered Lehigh University in July of 1989 to pursue a Masters of Science Degree in Civil Engineering. Since that time she has worked as a research assistant on two different projects. The first project to be completed was an econometric study of the life-cycle costing on steel and concrete bridges in the United States. For this project she was responsible for the technical facets. The second project was to determine the comparative effectiveness of 3 tightening methods of 1¼ inch diameter A490 bolts. Both projects were conducted in the Research Center for Advanced Technology for Large Structural Systems (ATLSS).